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برنامج الماجستير في تصميم وتأهيل المنشات

Performance of Recycled Aggregate Concrete

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DEDICATION

To the spirits of my parents, my brother the martyr Hassan and my brother Ali those was there for guidance and gave me the hope tools. I can make you as proud of me as I am of you. To my wife, the woman who has been and still encouraging, supporting and save the good conditions for me to go ahead in my thesis and looking for higher degree of science.

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I would like to extend a special thank to the Islamic University Labs team for thire effort in helping me during the experimental studies and to all of the people that made this project possible. This project would not have been possible without their help.

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ABSTRACT

Owing to the shortage of space for land reclamation in Gaza Strip, it is difficult to dispose tons of construction and demolition waste generated daily from construction activities and destroying of building during Israeli campaigns in addition to the huge amount of ex-settlements destroyed buildings. Adoption of recycled aggregate from concrete waste thus becomes a burning issue. For this reason, it is suggested that clearing the debris from destroyed buildings in such a way as to obtain recycled concrete aggregates to be reused in concrete production that could well be a partial solution to environmental pollution. For this study, the physical and mechanical properties of recycled aggregate concrete produced were investigated and tested.

Most of studies held in Gaza strip on recycled aggregate produced from construction and demolition wastes, focused on using recycled aggregate as granular material for base coarse roads and for concrete mixes for concrete hollow blocks .

This thesis, aims to find the possibility of the structural usage of recycled aggregate concrete in lieu or mixed with natural aggregates, based on better understanding of behavior of recycled aggregate in concrete structures. experimenting fresh and hardened concrete, mixtures containing recycled aggregates.

The percent of fine recycled aggregate in the all recycled aggregate was about 5.0% so it was excluded from the study. 0 %,30 % and 60 % of coarse recycled aggregate was used in the experimental tests . Two kinds of natural fine aggregates were used , Gaza sand and crushed stone .

The experimental tests focused on, physical properties density and workability, and mechanical properties compressive strength , flexural strength and bond strength between concrete and steel. More than 120 concrete specimens were tested for the study. The tests showed that the workability of recycled aggregate is lower than the workability of natural aggregate concrete ,the slump test was about 1.0cm slump for 60 % coarse recycled aggregate concrete and increases as the percent of recycled aggregate decreases . The compressive strength of recycled aggregate concrete with 60 % recycled aggregate, is about 76 % of natural aggregate concrete. The compressive strength increases as the percent of recycle aggregate in concrete mixes decreases. As the percent of Gaza sand increases the compressive strength of recycled aggregate concrete decreases for the same

percent of recycled aggregate . The concrete of recycled aggregate exactly behaves as natural aggregate concrete in flexural tests and the flexural strength have same percent of corresponding compressive strength ($3.2\sqrt{fc}$ kg/cm^2) . The bond strength between deformed steel bars of recycled aggregate concrete is about 1.4 times natural aggregate concrete.

Future studies on recycled aggregate are recommended, like the effect of mitigation of alkali and silica on recycled aggregate concrete, the durability of recycled aggregate concrete and the effect of fire on recycled aggregate. Developing specifications and standards are necessary in order to encourage use of recycled aggregate in lieu of natural aggregate.

الخلاصة

كما هو معروف فان قطاع غزة يعانى من صغر المساحة وضيق الأماكن اللازمة لطرح حطام المباني الناتج عن عمليات البناء والمباني التي هدمها جيش الاحتلال الصهيوني والمباني التي هدمت في المحررات .وبالتالي جعل موضوع استغلال الركام المعادة موضوعا ذا أهمية عالية.وبالتالي التعجيل فى حل مشكلة تراكم حطام المباني الذي يعتبر حل جزئي لمشكلة بيئية ولأجل حل هذه المشكلة اجريت هذه الدراسة لدراسة الخواص الفيزيائية والميكانيكية للركام المعاد.

معظم الدراسات التي أقيمت في قطاع غزة لدراسة موضوع إعادة استغلال الركام على موضوع الطرق واستخدام الركام كطبقات للطرق وكذلك استخدامها فى صناعة البلوك المستخدم في المباني

فى هذه الدراسة التي تركز على استخدام الركام المعاد لوحدها او بالاشتراك مع الركام الطبيعية فى إنشاء الأجزاء الخراسانية الإنشائية للمباني بالاعتماد على اختبارات للخرسانة المحتوية على الركام المعاد الاستخدام وهذه الاختبارات أجريت على الخرسانة المتميعة والخرسانة الجافة.

في هذه الدراسة تم اعتماد على ثلاث نسب من الركام المعاد وهى 60%و30%و0% وهذه النسب من الركام الخشن المعاد لان نسبة الركام الناعم فى الركام المعاد لم تتجاوز 5% لذلك لم يدرج الركام الناعم المعاد فى هذه الدراسة ولقد تم استخدام نوعين من الركام الناعم الطبيعي حسب نسبة رمل غزة وهذين النوعين تم خلطهما ليحققا المواصفات الامريكية (ASTM) .

وركزت التجارب فى هذه الدراسة على التجارب الفيزيائية مثل الكثافة والتشغيلية للخرسانة والتجارب الميكانيكية مثل قوة الضغط العمودي وقوة تحمل العزم وقوة التماسك بين الحديد و الخرسانة ولانجاز هذه التجارب تم تجهيز أكثر من 120عينة ولقد أثبتت هذه التجارب ما يلي تشغيلية الخرسانة الذي نسبة الركام المعاد فيه 60% كانت صفر وكلما قلت نسبة الركام المعاد كلم زادت التشغيلية ، قوة الضغط العمودي للخرسانة ذو 60% ركام معاد حوالى76% من الخرسانة ذو الركام الطبيعي وكلما قلت نسبة الركام المعاد كلما ازدادت قوة الخرسانة ، كلما ازدادت نسبة رمل غزة فى الركام الطبيعي كلما قلت قوة الخرسانة المستخدم فيه الركام المعاد قوة التماسك بين الخرسانة المعدة باستخدام الركام المعاد والحديد المجدل تزيد بمقدار1.4 ضعف عن الخرسانة المستخدم فيه الركام الطبيعي.

لاستخدام الركام المعاد بصورة عملية فإننا بحاجة لمزيد من الدراسات تشمل تأثير أملاح الكلوريد والكبريتات على الخرسانة المستخدم فيه الركام المعاد وبحاجة أيضا لدراسة الديمومة وعمل مواصفات خاصة بالركام المعاد

Chapter (1)

Introduction

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Introduction

Concrete is the premier construction material across the world and the most widely used in all types of civil engineering works, including infrastructure, low and high-rise buildings, defense installations, environmental protection facilities .

Since aggregate represents about 70-80 % of concrete components and Gaza imports their aggregate from out side, it is badly needs to recycle what is available of construction and demolition wastes in Gaza Strip to solve part of the problem and to solve also the environmental problem.

The use of recycled aggregates in concrete opens a whole new range of possibilities in the reuse of materials in the building industry. The utilization of recycled aggregates is a good solution to the problem of an excess of waste material, provided that the desired final product will fit the standards. The studies on the use of recycled aggregates have been going on for 50 years. In fact, none of the results showed that recycled aggregates are unsuiTable for structural use[1].

Recently the use of recycled concrete as a structural fill material, in lieu of natural aggregate, has recently been increasing. In some regions, recycled concrete aggregate may cost 20 % to 30 % less than natural aggregate [1].

1.1 Problem Statement

Gaza Strip is a small closed coastal area (365 Km^2) and a densely populated area with population of 1,443,814 according to year 2006 statistics. The disposal of construction and demolition wastes in Gaza Strip is one of the challenging problems; due to the scarcity of open lands and the limited size of municipal dumping sites to accommodate large quantities of debris and unprocessed construction wastes. The random and uncontrolled disposal of construction and demolition wastes creates several environmental impacts. A survey by the Islamic University of Gaza in 2002 indicated that more than 1 million m^3 of construction and demolition wastes are distributed over 21 main sites in Gaza Strip. The most recent assessment of the construction and demolition wastes quantities in Rafah and Khan Younis are estimated at about 0.25 million m^3 [2].

Aggregate produced from recycled concrete is badly needed in Gaza Strip to reduce the import of natural aggregate materials, transportation cost, improved profits and to improve the environment by reducing wastes.

The construction and demolition waste comprises 23% to 33% of municipal solid wastes. Some estimates put concrete, asphalt, and rubble at about 50% of the construction and demolition wastes by weight [3].

The environmental problems in Gaza strip are immense; it is one of the places in the world where the exploitation level of resources exceeds the carrying capacity of the environment. This is especially true for the land resource, which are under high pressure of prone to serve over-exploitation.

The disposal of construction and demolition wastes in Gaza Strip is one of the challenging problems; due to the scarcity of open lands and the limited size of municipal dumping sites to accommodate large quantities of debris and unprocessed construction wastes. The random and uncontrolled disposal of construction an demolition wastes creates several environmental impacts.

In this research, recycled aggregate has been investigated to be as concrete fillers instead of natural aggregates or combined with it to produce concrete mixes to be used in concrete structural elements . By recycling of construction and demolition wastes the environmental impact can be minimized to the lowest level and natural resource of aggregates will be saved.

1.2 Aim and objective:

This research aims to reduce the environmental problems generated from dumping the construction and demolition wastes. This aim can be achieved by recycling the construction and demolition wastes to produce concrete mixes for structural elements with high performance as natural aggregate.

Objectives:

1. Studying the physical and mechanical performance of recycled aggregate used in concrete mixtures in lieu of natural aggregate.
2. To examine the possibility of using recycled aggregate in concrete mixes.
3. To investigate the bonding strength between reinforcement bars and concrete from recycled aggregate.
4. To study the admixtures that can be added to enhance the bond between the recycled aggregate and the cement paste on one side, and the bond between the concrete and the reinforcement steel from the other side.
5. To optimize the ratio of recycled aggregate to natural aggregate to produce better concrete mix.

1.3 Methodology:

The following tasks are done to achieve research objectives:

1. Collection of all information and studies related to the construction and demolition wastes in Gaza Strip.
2. Site visit to the construction and demolition wastes dumping and crushing sites.
3. Bringing samples of the recycled aggregate from the crushing sites.

4. Clean, wash and dry the recycled aggregate samples.
5. Making sieve analysis of the recycled aggregate samples and natural aggregate at the Islamic University Material and Soil Laboratory.
6. Prepare the concrete mixes with appropriate percentages of natural aggregate and recycled aggregate.
7. The following tests were conducted:
   - Slump test for all the specimens.
   - Compressive strength at7and 28 days
   - Pull out test
   - Flexural test
8. Summary and conclusion of the test results and recommendation for future tests.

1.4 Thesis Overview

This thesis is structured in the following format.

- Chapter 2 provides overview of recycling process and the use of recycled aggregate all over the world
- Chapter 3 illustrates the sources of recycled aggregates and its use in Gaza Strip .
- Chapter 4 describes the experimental methodology carried out in order to obtain the required data, includes the preliminary design and information on the recycled aggregate testing, sieve analysis and design of the concrete mix.
- Chapter 5 discusses the results and analysis of all experimental results obtained from the testing procedures.
- Chapter 6 contains the conclusions of the research and recommendations for further work.

Chapter (2)

Literature Review

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Literature Review

The quality of concrete made from recycled aggregate is generally lower than that of concrete made from natural aggregate. The main reason for this is that recycled aggregate with its higher water absorption capacity has a porous mortar matrix around the natural aggregate and hence develops an inferior bond [4].

Although of low quality of recycled aggregate, recycled aggregates have long been used in the construction industry, however, due to lack of suitable specifications, their use is being limited to the low grade applications. Undoubtedly, suiTable quality recycled aggregates may be used successfully in higher grade applications such as structural concrete. Recent international advances in the drafting of specifications now provide good guidance on the quality control of recycled aggregates and their use in higher grade applications [5].

Many studies were constructed on recycled aggregate concrete all over the world, and locally in Gaza Strip these studies included the behavior of recycled aggregate concrete in fresh and hardened case.

2.1 Studies on Recycled Aggregate

2.1.1 World Wide Studies

Recycled aggregate concrete passing 4.76 mm sieve is not recommended for general use in concrete because it usually has an adverse effect on water demand and may contain increased levels of contamination. In specific circumstances where there is a high degree of control (e.g. fines from reclaimed product at a precast concrete works), 10% replacement of natural sand can be made without adverse effect on the product.. Fine recycled aggregate may also be useful for large scale grouting operations (eg old tunnels and mine workings) [6].

Recycled aggregates ,particularly recycled masonry aggregates, typically have a higher porosity than natural aggregates. Because of this, concrete with recycled aggregates absorbs a higher amount of moisture than ordinary concrete. Also the angularity of the crushed material contributes to a high water requirement. However, by pre-wetting the aggregate, or by partly saturating the aggregate in the concrete mixer prior to the addition of cement, the recycled aggregate concrete will result with properties similar to those of ordinary concrete mixes, prepared with a comparable water/cement ratio [7].

As a rule, the workability of concrete with a high level of aggregate replacement is low. This is especially so, if also the fraction 0-4 mm is replaced. Adding water may increase workability, but will have adverse influence on the strength and the durability of the resulting concrete. Generally, the addition of some more super plasticizer will be sufficient. A common alternative is to increase both water and cement, thereby keeping the water/cement ratio constant [7].

The relatively high water demand of recycled aggregates will have their impact on shrinkage. However, due to the moisture absorption in the recycled masonry aggregates, concrete made with this aggregate may even display less shrinkage in the initial stages of hydration. In case of total replacement of natural aggregates by recycled masonry aggregates, ultimate shrinkage may on average be about 40% higher. Concrete with recycled masonry aggregates also presents an increased creep (15-40%) and a decreased modulus of elasticity (10-30%) [7].

A full replacement of the coarse and fine aggregate fraction in concrete by 0-40 mm recycled aggregates generally lowers the compressive strength by about 20%. If only the fraction larger than 4 mm is being applied, the decrease in strength may be limited to about 10% [7].

The recycled aggregate concrete can provide strength equivalent to a corresponding concrete with natural aggregates, provided the cement content is increased, typically by 7.2% for 40 MPa concrete. The compressive strength of the recycled concrete incorporating brick as aggregate is not reduced until an incorporation of 40% or more [7].

Researches at the University of Dundee indicated that with up to 30% coarse or 20% fine recycled concrete aggregate content, the effect on concrete compressive strength is negligible. However, a further increase in percentage will result in reduced strength. To achieve recycled aggregate strength equivalent to corresponding natural aggregate concrete, is to change the water/cement ratio of the concrete mix with high levels of recycled aggregate content [8].

The compressive strength of recycled aggregate concrete is also effected by the quality of recycled aggregates. Low-quality recycled aggregate consists of crushed concrete, asphalt, brick and other deleterious material adversely affects the compressive strength of the recycled aggregate concrete. However, research project in UK indicated that concrete of a characteristic strength of 45 MPa with a slump in the range of 150-175 mm could be produced in the laboratory by replacing 60% of the natural coarse aggregate by mixed recycled aggregate collected from a demolition contract [9].

The tensile splitting strength is only marginally less compared to concrete with natural aggregates. However, when recycled masonry aggregates are used, the bending tensile strength of the concrete can be reduced to 50-60% of that in ordinary concrete [7].

The bond strength between steel and recycled aggregate concrete is found to be equivalent to that of conventional concrete both under static and fatigue loading, where coarse recycled aggregates were used with natural sand. However, when both fine and coarse recycled aggregates were used, cracks appeared at 15% lower flexural load then when conventional aggregates were used, and the ultimate flexural strength of reinforced concrete was 30% lower due to bond failure. Shear strength followed a similar pattern [10].

Jianzhuang Xiaoa et al concluded in 2004 after experimental results for the mechanical properties of recycled aggregate concrete under uniaxial compression loading [11]:

- The failure mode of recycled aggregate concrete is a shear mode under the experimental conditions of their study mechanical properties of recycled aggregate.

The failure process of recycled aggregate concrete is relatively short. The inclination angle between the failure plane and the vertical load plumb is about 63–79^{O} .

- The recycled aggregate replacement percentage has a considerable influence on the stress–strain curves of recycled aggregate concrete. For all considered cases from recycled aggregate from 0% to 100%, the stress– strain curves show a similar behavior. The stress– strain curves of recycled aggregate concrete indicate an increase in the peak strain and a significant decrease in the ductility as characterized by their descending portion.
- The compressive strengths including the prism and the cube compressive strengths of recycled aggregate concrete generally decrease with increasing recycled aggregate contents. But the ratio of the prism compressive strength and the cube compressive strength is higher than that of the normal concrete.
- The elastic modulus of recycled aggregate concrete is lower than that of the normal concrete. It decreases as the recycled aggregate content increases. For a recycled aggregate replacement percentage equals 100%, the elastic modulus is reduced by 45%.
- The peak strain of recycled aggregate concrete is higher than that of normal concrete. It increases with the increase of recycled aggregate contents. For a recycled aggregate replacement percentage equals 100%, the peak strain was increased by 20%.

Nelson, Shing Chai NGO stated the following in their work on high-strength structural concrete with recycled aggregates [12]:

- The workability was good and can be satisfactorily handled for 0% recycled aggregate to 80% recycled aggregate. The slumps from 0% recycled aggregate to 80% recycled aggregate were considered moderate due to the drop in the range of 5mm to 0 mm.

- The average of compacting factor ratio for 0% recycled aggregate to 80% recycled aggregate is 0.996. The average of compacting factor ratio for 100% recycled aggregate (with 0.43 water cement ratio) and 100% recycled aggregate (with fly ash cement) is 0.973. There is no problem in handle and compact the fresh concrete in these batches.

- The compressive strength for 20% recycled aggregate replacement had dropped around 15%. The concrete specimens from 0% recycled aggregate to 80% recycled aggregate replacement had the average drop of 8%. There is a drop of 21% compressive strength for the 100% recycled aggregate (0.43 water/cement ratio), where it only drops 5% of compressive strength for 100% recycled aggregate (0.36

water/cement ratio). The main reason is because of the lower water cement ratio and also the particular size of recycled aggregate used in this batch is smaller than other concrete specimens From the obtained result, it is possible to use 100% recycled aggregate with the less water cement ratio in the high strength structures.

- From the result, it clearly shows that with more percentage replacement of recycled aggregate used in the concrete specimen, the percentage of tensile strength remained are gradually decreasing. The tensile strength will remain higher when the water/cement ratio is getting lower.
- From the experimental results, the modulus of elasticity of full natural aggregate specimens was 44303MPa, while the modulus of elasticity of full recycled aggregate specimens was 26422MPa. It indicates a drop of 17881MPa, which is 67% difference between the 0% and 100% recycled aggregate batches. Additionally, the difference with each 20% recycled aggregate increase is approximately 21%.

Pilar Alaejos Gutiérrez and Marta Sánchez de Juan has investigated after construction many tests in their research Utilization of Recycled Concrete Aggregate for Structural Concrete [13]:

- Coarse recycled aggregates were found to have very low contents of both sand (0.5-1.9%) and fines (0.3-1.2%), but it is due, as we said before, to the sampling process
- The range of density obtained is 2.100-2.400 kg/m^3, in all cases the coarser fraction shows higher density.
- The water absorption of coarse recycled aggregates range from 4,8% up to 9,6%, and has a variation coefficient of 25.5%. The results of chemical analyses indicate that recycled aggregates tested present suitable chloride and sulphate ion content.

In their final report , Crushed Returned Concrete as Aggregates for New Concrete in 2007 ,Karthik Obla Haejin, et al stated that [14]:

- Recycled concrete aggregate has higher water absorption rates than natural aggregates. Higher absorption rates are indicative of higher volume fractions of old cement mortar adhering to the natural aggregate particles in the original concrete.
- As recycled aggregate concrete content in concrete mixtures increases, their workability decreases. In order to produce similar workability as natural aggregate concrete , 5% more mixing water was required when using just the coarse fraction of recycled concrete aggregates and up to 15% more mixing water when using both the coarse and fine fractions of recycled aggregate. Issues of workability are largely tied to the inclusion of recycled fines in recycled aggregate concrete. For that reason, it is recommended that fine recycled aggregate levels remain at or below 30% of total fine aggregate content[1]. Entrapped air contents of non-air

entrained concrete containing recycled aggregate were up to 0.6% higher and varied more than air contents of non-air entrained control mixtures4. The density of concrete made using recycled aggregate was found to be within 85%-95% of the natural aggregate concrete. Finish ability of concrete containing recycled aggregate is generally adversely affected.

- Compressive strength of concrete containing recycled aggregate is dependent upon the strength of the original concrete from which the recycled aggregate was made. Concrete's compressive strength gradually decreases as the amount of fine recycled aggregate increases. The reduction is reported to be between 5% and 24% when just coarse recycled aggregate was used and between 15%-40% when all of the recycled aggregate (including the fine fraction) was used.
- Strength reduction becomes more significant when the fine recycled aggregate content surpasses 60% of the total fine aggregate. recycled aggregate concrete has around the same or 10% less flexural strength than concrete containing natural aggregate. However, some studies have found that with the incorporation of fine recycled aggregate the reduction in flexural strength can be as much as 10%-40%.
- Creep of concrete is proportional to the content of paste or mortar in it. To that end, it is understandable that recycled aggregate undergoes increased creep because it can contain about 70% more paste volume than concrete made with virgin aggregate, with the exact amount dependent upon the amount of recycled aggregate replacing the natural aggregate, and paste volume in the recycled aggregate and the new concrete. Researchers have observed creep to be 30%-60% greater in concrete manufactured using recycled aggregate compared to concrete with natural aggregate. Like creep, increased shrinkage rates are also related to increases in cement paste contents.
- Shrinkage rates are still dependent on the amount of recycled aggregates used, the 1 year values are comparable to that of concrete containing natural aggregate. Other studies have shown more differentiation in drying shrinkage values. One study showed that concrete made with recycled aggregate resulted in 70%-100% greater shrinkage. The same study also reported that concrete made using coarse recycled aggregate along with natural sand increased shrinkage by only 20%-50%.

The bond behavior between steel bars and recycled aggregate concrete has been tested and studied by many researchers Jianzhuang Xiao and H. Falkner in their studies in bond strength behavior stated [15]:

The general shape of the load versus slip curve between recycled aggregate concrete and steel rebars is similar to the one for normal concrete and steel rebars, which includes micro-slip, internal cracking, pullout, descending and residual stages. Under the condition of the equivalent mix proportion and compared with that of normal concrete, the bond strength between the recycled aggregate concrete and the plain rebar decreases by 12% and 6% for an recycled aggregate replacement percentage of 50% and 100%, respectively; while the bond strength between the recycled aggregate concrete and the deformed rebar is similar, irrespective of the recycled aggregate replacement percentage. For the case of the same compressive strength, the bond strength between the recycled aggregate concrete with 100% recycled aggregate and steel rebars is higher than the one between normal concrete and steel rebars. For the recycled aggregate concrete, the bond strength between deformed steel rebars and concrete is approximately 100% higher than the one between plain steel rebars and concrete, and the coefficient of variation for the bond strength of the plain steel rebar is much higher than the one for the deformed steel rebar. The anchorage length of steel rebars embedded in the recycled aggregate concrete with recycled aggregate is 100% can be chosen as the same for normal concrete under the condition of the same compressive strength of concrete.

2.1.2 Local Studies

Locally, several limited research were conducted to investigate the applicability of recycled aggregate in engineering applications, three fields covered were; concrete mixes, roads construction and hollow block production. The main findings were:

- Concrete made with recycled aggregate produced from construction and demolition waste has a compressive strength (28days) about 27% - 30% less than the strength of the concrete made with natural aggregates[16].
- No swelling is noticed in any CBR test. The results of physical tests indicate the applicability of recycled aggregate in road constructions [16].
- Concrete Hollow Blocks made with recycled aggregate has compressive strength about (12 – 21)% less than that of concrete hollow blocks made with natural aggregate. And for the same compressive strength the cost of with recycled aggregate is less than the cost of those with natural aggregate [16].

Many other researches were conducted locally to study the quantities and sources of construction demolition wastes and the behavior of recycled aggregate :

- The estimated generation rates of construction and demolition waste in Gaza strip have reached more than 0.625 M^3 per year rather than 1.5 million M^3 were generated due to Israel destruction in ex-settlements and Palestinian homes in Gaza strip[17].
- The specific gravity of recycled aggregate concrete is relatively less than natural aggregate because of existing cementations materials which is high porosity material[18].
- Concrete results showed that 25MP and 30MP strength can be reached using recycled aggregate as a coarse material. Fine material must not have more

than30.0% of fine recycled aggregate. Using more than 35% of fine recycled aggregate causes an obvious weakness in the concrete strength [18].

- Because of the rapid absorption of recycled aggregate the workability of the fresh concrete is relatively low ,especially after 15 min of the casting process[18].
- Concrete made with recycled aggregates has a compressive strength about 22%-32% less than the strength of the concrete made with natural aggregates [19].

2.2 Production and Sources of Recycled Aggregate

Recycled aggregate is produced as a result of crushing, graded inorganic particles processed from the materials that have been used in the constructions and demolition debris as shown in Figure (2.1). These materials resulted from destruction of buildings, roads, bridges, and sometimes even from catastrophes, such as wars and earthquakes.

Figure (2.1) :Recycled Aggregate

2.2.1 Recycling Plant

Recycling plant normally located out side cities due to the noise pollution resulting from the equipment that used during recycling process. Figure (2.2) shows the process that is used in producing the recycled aggregate ,the process starts from the demolished construction site ,ending in ready recycled aggregate for use [20].

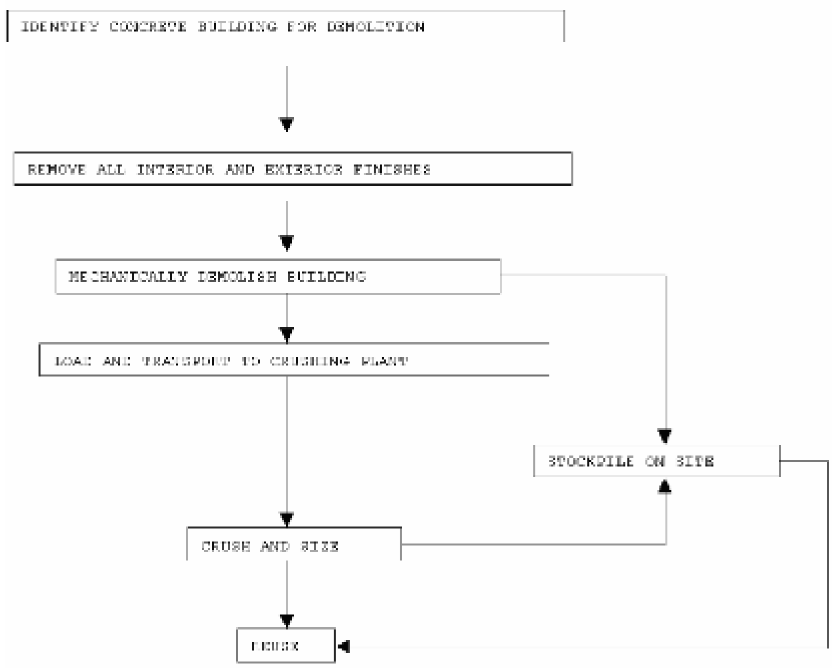

Figure (2.2):Recycling Portland cement concrete flow process [20]

As shown in the previous Figure(2.2) , the processes of recycling of construction and demolition wastes are similar to those producing natural aggregates , both have the same equipments,crushers,screens,removal impurities and transportation facilities. Two types of recycling plants are used widely all over the world:

1. Stationary recycling plant
2. On-site recycling.

Both types have the same process scheme ,but the stationary plant is located in a far areas away of cities and urban areas. The equipments in the first type is very big ,noisy and needs very qualified roads to carry heavy loads. The second type is small and movable and can be located in the demolished site. The crushing plant will be explained in detail.

2.2.2 Sources of Recycled Aggregate

The aggregates that can be produced from the breakup and crushing of existing portland cement concrete pavement and structural elements is called recycled aggregate. There are two sources of demolished concrete all over the world :

a. Rigid concrete pavement: where an asphalt concrete surface is present on an existing rigid pavement, the asphalt concrete must be removed before the old Portland cement concrete pavement is broken up [20] .

b. Concrete structures: It is the intention of this operation to produce the maximum amount of Portland cement concrete that can be crushed, stockpiled, and accepted as aggregate in new Portland cement concrete. All reinforcing steel should be removed from the concrete either prior to or during the crushing operation[20].

2.3 Equipment used during Recycling Process

2.3.1 Break up equipment

There are few different types of equipments that had been used effectively to break up the old cement pavement and structural building.

2.3.1.1 Portland Cement Pavement break up equipment

(1) **Driving hammer**. It is mounting on a motor grader that sticks in the Portland cement pavement on around 30cm grid pattern[20].

(2) **Horn – tooth – ripper –** equipped hydraulic excavator. It is used to remove all the steel reinforcement that remaining in the Portland cement pavement[20].

2.3.1.2 Structural Building break up equipment

The following methods had been used to crush the structural building:

(1) Mechanical by hydraulic crusher with long boom arm:

The concrete and steel reinforcements are broken by the crusher through the long boom arm system. This method is suitable for the dangerous buildings. Hong Kong Building Department mentioned that the following methods had been used to crush the structural building[21].

(2)Wrecking ball.

The building is demolished by the impact energy of the wrecking ball which suspended from the crawler crane[21].

(3)Implosion. A design included pre – weakening of the structure, the placement of the explosives and the building collapse in a safe manner have to develop[22].

2.3.2 Transportation of demolished construction waste equipment

After the structural buildings and Portland cement pavements are demolished, the concrete debris have to be sent to the recycling plants for processing. Construction and Demolition Waste Recycling Information mentioned that it is good to use the roll – off containers or large dump body trailers to transport the mixed load of construction and demolition debris. This is the most effective and cost effective means of the transportation. It also mentioned that the construction and demolition debris can be transported by the closed box trailers and covered containers.

2.3.3 Crushing Plant equipment

Crushing is the initial process of producing the construction and demolition debris into recycled aggregate. The concrete debris is crushed into pieces in this process. The equipment used for crushing process are either jaw or impacted mill crushers. All the recycling crushers have a special protection for conveyor belts to prevent damage by the reinforcement steel that in the concrete debris. They are fitted with the magnetic conveyors to remove all the scrap metal. The equipment used to crush and size the existing concrete have to include the jaw and cone crushers as shown in Figure(2.3). The concrete debris will break down to around 3 inches by the primary jaw crusher. The secondary cone crushers will breaks the materials to the maximum size required which vary between ¾ and 2 inches [23].

Figure(2.3):Load into Primary Crusher

During the crushing process, all the reinforcing steels have to be removed .There are three methods of sorting and cleaning the recycled aggregate, which are electromagnetic separation, dry separation and wet separation. Electromagnetic separation process is removal of reinforcing steel by the magnet that fitted across the conveyor belt in the primary and secondary crushers as shown in Figure(2.4) . Dry separation process is removing the lighter particles from the heavier stony materials by bowing air as shown in Figure(2.5). This method always causes lot of dust. Wet separation process is the aquamator, which the low density contaminants are removed by the water jets and float – sink tank as shown in Figure(2.6) , and this will produces very clean aggregate. the wood pieces that contained in the concrete debris can be removed by hand – picking from a special platform over the discharge conveyor. After finishing the crushing process, the materials are then sent to the screening plant[23].

Figure(2.4):Electromagnetic Separation Process

Figure(2.5):Picking Shed

Figure(2.6):Wet Separation Process

2.3.4 Screening Plant and Washing Plant equipment

Screening is the process that separates the various sizes of recycled aggregate. The screening plant shown in Figure (2.7) is made of a series of large sieves separates the materials into the size required. Recycling of portland cement concrete stated that the size of screen that used to separate the coarse recycled concrete aggregate and fine recycled aggregate is 3/8 inch. The size of screen used to separate the coarse recycled aggregate can be under or over ¾ inches. One more screen should be used to separate those particles that more than the specified size. After the screening process, the recycled aggregate are then sent to the washing plant as shown in Figure (2.8). The recycled aggregate that produced have to be very clean when using in the high quality product situation [23].

Figure(2.7):Screening Plant

Figure(2.8):Washing Plant

2.4 Stockpiling

After all the recycling process, recycled aggregate are stored in the stockpile and ready for use. All the recycled aggregate are stored according to the different size of aggregate. The stockpile has to prevent from the contamination of foreign materials. It also mentioned that the vehicles used for stockpiling have to be kept clean of foreign materials [23].

2.5 Application of Recycled aggregate concrete world wide

Traditionally, the application of recycled aggregate is used as landfill. Nowadays, the applications of recycled aggregate in construction areas are wide. The applications are different from country to country.

1-Concrete Krebs and Gutter Mix

Recycled aggregate have been used as concrete kerb and gutter mix in Australia. according to Building Innovation & Construction Technology (1999) [24]. The 10mm recycled aggregate and blended recycled sand are used for concrete kerb and gutter mix in the Lenthall Street project in Sdyney[24].

2- Granular Base Course Materials

Recycled aggregate are used as granular base course in the road construction. The recycled aggregate had proved that better than natural aggregate when used as granular base course in roads construction. Also it was found that when the road is built on the wet subgrade areas, recycled aggregate will stabilize the base and provide an improved working surface for pavement structure construction[25].

3- Embankment Fill Materials

Market Development Study for Recycled Aggregate Products (2001) stated that recycled aggregate can be used in embankment fill. The reason for being able to use in embankment fill is same as it is used in granular base course construction. The embankment site is on the wet sub grade areas. Recycled aggregate can stabilize the base and provide an improved working surface for the remaining works[25].

4- Paving Blocks

Recycled aggregate have been used as paving blocks in Hong Kong. According to Hong Kong Housing Department , recycled aggregate are used as typical paving blocks. A trial project had been started to test the long – term performance of paving blocks made with recycled aggregate in 2002[26].

5-Backfill Materials

Recycled aggregate can be used as backfill materials. Norwegian Building Research Institute (2001) mentioned that recycled concrete aggregate can be used as backfill materials in the pipe zone along trenches after having testing in laboratory[27].

6- Building Blocks

Recycled aggregate has been used as building blocks. In 2001 recycled aggregate has been used to produce the masonry sound insulation blocks. The masonry sound insulation blocks that produced had met all the requirements during the laboratory testing. [27].

7- Reinforced concrete building

. Recycled concrete aggregate had been used in constructing a new high school, outside the city of Oslo, Norway in 2001 as shown in Figure(2.9). Thirty – five percent of coarse aggregate were replaced by recycled concrete aggregate in the foundations, half of the basement walls and columns. Several tests were conducted based on fresh and hardened concrete properties and the results shown that the concrete with thirty – five percent of recycled concrete aggregate have good freeze – thaw resistance. The use of recycled concrete aggregate did not shown any noticeable increase in cracking[27].

Figure(2.9):Construction of the New High School in Sorumsand, Oslo, Norway

2.6 Conclusion

Recycled aggregates are used extensively in civil construction projects ,including the production of portland cement concrete, granular sub-base for road construction ……….etc.

It is apparent that there is general concern within the industry of using the recycled building materials, specially recycled aggregate.

Let us imagine if the construction and demolition wastes were remained without reuse , mountains of construction and demolition wastes will appear all over the world and consequently very serious environmental problem will happen. Full use of recycled aggregate produced from construction and demolition wastes, the problem of construction and demolition wastes will disappear, saving energy of producing natural aggregate and finally keeping the natural resources .

In local studies ,the fine aggregate was used is only Gaza Sand which doesn’t lead to good results as expected and at the same only compressive strength test was constructed. The behavior of recycled aggregate in flexural and bond strength wasn’t tested. The property of recycled aggregates in Gaza Strip differs than the property of recycled aggregate world wide. In this study we are going to cover this gap.

Chapter 3

Recycled Aggregate in Gaza Strip

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Recycled Aggregate in Gaza Strip

3.1 Introduction

The problem of construction and demolition wastes has appeared obviously at the beginning of the year 2005, after the withdrawal of Israeli occupation and the rapid continuous campaigns of destroying buildings and infrastructure in Gaza Strip. Figure (3.1) shows the map of Gaza Strip, with the locations of cities and ex-settlements [28].

Figure(3.1): Gaza Strip map shows the location of cities and ex-settlements

The rapid development of construction industry around the world in the last five decades after the second world war led to generate huge quantities of construction and demolition waste materials. In Gaza Strip, this problem started after Oslo agreement 1994 which led the acceleration in the construction industry; and rapidly increasing after the beginning of Al-Aqsa Intifadi in September 2000. The Israeli military responded to Alaqsa intifida by systematic destruction of houses, roads, bridges, agricultural lands and bombardment of public building and Palestinian Authority head quarters. Demolition of Israeli houses in settlement during the disengagement from the Gaza in August 2005 increased the problem of construction and demolition waste in Gaza Strip.

The disposal of construction and demolition wastes in Gaza Strip is one of the challenging problems; due to the scarcity of open lands and the limited size of municipal dumping sites to accommodate large quantities of debris and unprocessed construction wastes. The random and uncontrolled disposal of construction and demolition wastes creates several open dump sites as shown in Figure(3.1).

Figure(3.2): Random and uncontrolled disposal of construction and demolition wastes at Gaza beach

The problem of construction and demolition waste increased after the withdrawal of Israeli occupation from Gaza Strip as a result of Israeli policy of destruction and demolition of homes and buildings in settlements. Ten thousands tons of construction and demolition wastes were added to the existing dumped locally.

3.2 Sources and Quantities of Construction and Demolition wastes In Gaza Strip

There are no studies on construction and demolition waste generation rates in Gaza Strip. However, the international available data shown in Table (3.1) does allow predicting the amount of construction and demolition waste generated yearly in Gaza Strip.

Table(3.1) shows that construction and demolition waste generation is around 0.5 ton per capita per year. So we can assume generation rate of construction and demolition waste in Gaza Strip is around 0.5 ton per capita per year and since the population of Gaza strip is around 1.5 million, so there will be 0.75 million ton generated per year in Gaza strip in normal situations[17] .

Three main sources of construction and demolition waste are in Gaza Strip:

1. Construction and demolition waste generates from new construction sites, structure renovation, structure demolition road repair sites, razing of buildings, and broken pavement. A survey by the Islamic University of Gaza in 2002 indicated that more than 1 million m^3 of construction and demolition wastes are distributed over 21 main sites in Gaza Strip [29].
2. Construction and demolition generates from destroying buildings due to Israeli military actions. The number of houses was destroyed during Israeli military actions is shown in Table 3.2.

3. Huge quantities of construction and demolition was generated as a result of destroying Israeli settlement during the withdrawal from Gaza Strip . The Ministry of Civil Affairs estimated this quantity 356000.0 tons-178000.0 m^3[30].

Table(3.1): Construction and demolition waste quantity generation rates in some countries around the world.

No.	Country Name	construction and demolition waste rate per Capita/ year	Reference
1	EuropeanUnion	0,5 – 1 ton	Lauritzen, 2004
2	United states	1 ton	Lauritzen, 2004, LaCrossa and Graves, 2002
3	Brazil	0.5 ton	John et al, 2004
4	Denmark	0.506 ton	Baum and Kats, 2003
5	Israel	1 ton	Israel min. of environmental protection
6	Sweden	0.66 ton	Baum and Kats, 2003
7	Egypt	0.52 ton	Egyptian ministry of environment
8	Iceland	0.6 ton	Baum and Kats, 2003
9	Gaza Strip	.26 ton	Islamic University of Gaza

Table (3.2): Number of destroyed houses in Gaza Strip[18]

City	Rafah	Khan-Youns	Dair-Elbalah	Nuseirat	Bureij	Gaza	Jabalia &North Area
Houses Destroyed	1455	649	100	86	16	45	197

3.3 Production of the Recycled Aggregate in Gaza Strip:

In Gaza Strip , the second type of concrete recycling is used, as shown in Figure (3.3)because of small area , limited economic facilities and unsuiTable facilities .

Figure (3.3): Rafah Municipality recycling plant near the Egyptian border

In fact, the effort for recycling of construction and demolition waste has rapidly increased due to many factors like closures and economic situation after Al-Aqsa intifada.

In Gaza Strip ,two sectors produce recycled aggregate:

1. **Public sector:**
   - Rafah Municipality recycling plant: Rafah municipality crushing machine were donated by the Italian government to help the city of Rafah to recycle the huge amounts of destruction waste with crushing capacity of 50 ton per hour, after few months the Italian government donated another crusher with large scale capacity of 240 ton per hour[17].
   - United Nation Development Program UNDP is planning to bring crusher with a capacity of 300 Ton per hour through the program of recycling the

ex-settlement debris and removal, and between eight to ten months all the sorted debris will be completely crushed as planned. Actually, the crushing process has started by sorting and separation for all components of demolition waste like concrete, block, steel, wood, clay tiling and hazardous material like asbestos which need special separation, then the big component which greater than 50 cm in any dimension like columns, slabs and foundations will be demolished by mechanical hammer. As a result of Israeli closure to Gaza Strip, the remaining equipment is still at the border so the project is put on hold.

2. **Private sector:**

- Shortage of aggregate quantities and its high cost lead some owners of concrete hollow block factories to find alternative materials. For example, in Al-Zawaida at Salah Eldain Street there is a concrete hollow block factory produces hollow block using recycled aggregate. This aggregate is obtained by crushing demolished hollow block using an electrical small crushing machine locally manufactured with a capacity of crushing 1.5 ton per hour and this crushed block are reused in manufacturing new hollow block as shown in Figure(3.4).

Figure(3.4):Hollow block factory using crushing machine for recycling aggregate in Al-Zawaydah.

3.4 Uses of Recycled aggregate in Gaza Strip:

All the quantity of aggregate used in all construction projects are imported from the West Bank ,since Gaza Strip has no sources to produce aggregate **.** As a result of the continuous closure of Gaza border by the Israeli occupation since the beginning of Second Intifida, most of construction projects stopped. This led to the use of other sources to produce aggregate, also since recycled aggregate material can be used within the same metropolitan area, this can lead to a decrease in energy consumption from hauling and production aggregate, and can help improve air quality through reduced transportation source emissions . The recycled aggregate was used in the following aspects:

1. Hollow blocks: Concrete hollow blocks is one of the practical applications for recycled aggregate concrete ,and it is known as the first application of recycled aggregate concrete . It is relatively easy and practical to use and don't need special equipments like other applications . It is high benefits to manufacture recycled aggregate hollow blocks compared to the natural concrete hollow block. At the same time the hollow block is used in parition walls not structural element in construction project. The tests held in Islamic University laboratory were enough to encourage engineers and contractors to use recycled aggregate hollow blocks .
2. Road Construction: Recycled aggregates can be considered as a good alternative to natural aggregates especially in road construction. Most of the characteristic test results were within the standard limits. The results of the tests that concern road applications were very good and verified the adequacy of materials[31].

Based on the previous studies of the Islamic University and other studies held by UNDP (United Nations Development Program),contractors and municipalities were encouraged to use the recycled aggregate products from recycling plant for road construction in Gaza Strip .

3.5 Future of Recycled Aggregate in Gaza Strip:

The quantity of construction and demolition wastes is very huge in comparison to small area of Gaza Strip. Imagining the quantity after three or four decades when old constructions has to be demolished, what will happen to the Gaza Strip.

In Gaza Strip recycled aggregates can be used in concrete hollow blocks, road construction as stated previously, but the recycled aggregate is still very huge;so it should be used in other uses other than stated. Recycled aggregate should be used in concrete structures instead of natural aggregates to accommodate the huge quantity of recycled aggregate. The full use of recycled aggregates solves the serious environmental problem ,save energy and save natural resources .

This study aims at determining the strength characteristics of recycled aggregate for potential application in the structural concrete to complete what has been done in this aspects.

Chapter 4

Materials And Experimental Program

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Materials And Experimental Program

In general, aggregates make up 60%-75% of the total concrete volume, so their selection is important, because they control concrete properties [32]. Hence, the selection and proportioning of aggregate should be given careful attention. Since recycled aggregate has a larger amount of porosity and can potentially undergo higher degree of deformation and will be weaker than the cement paste, therefore,it can greatly affect the mechanical and physical properties of concrete [33].

4.1 Materials

The materials were used in the test program, ordinary portland cement, natural coarse aggregate, recycled coarse aggregate , sand, natural crushed stone, water and super plasticizer. Material properties were as follows:

4.1.1Cement

Portland cement type I was used throughout the investigation. The cement was obtained from local concrete manufacture and kept in dry location. The cement source is Silo Nisher.

4.1.2Water

Tap water, potable without any salts or chemicals was used in the study. The water source was the soil and material laboratory in Islamic University Gaza.

4.1.3Admixture :

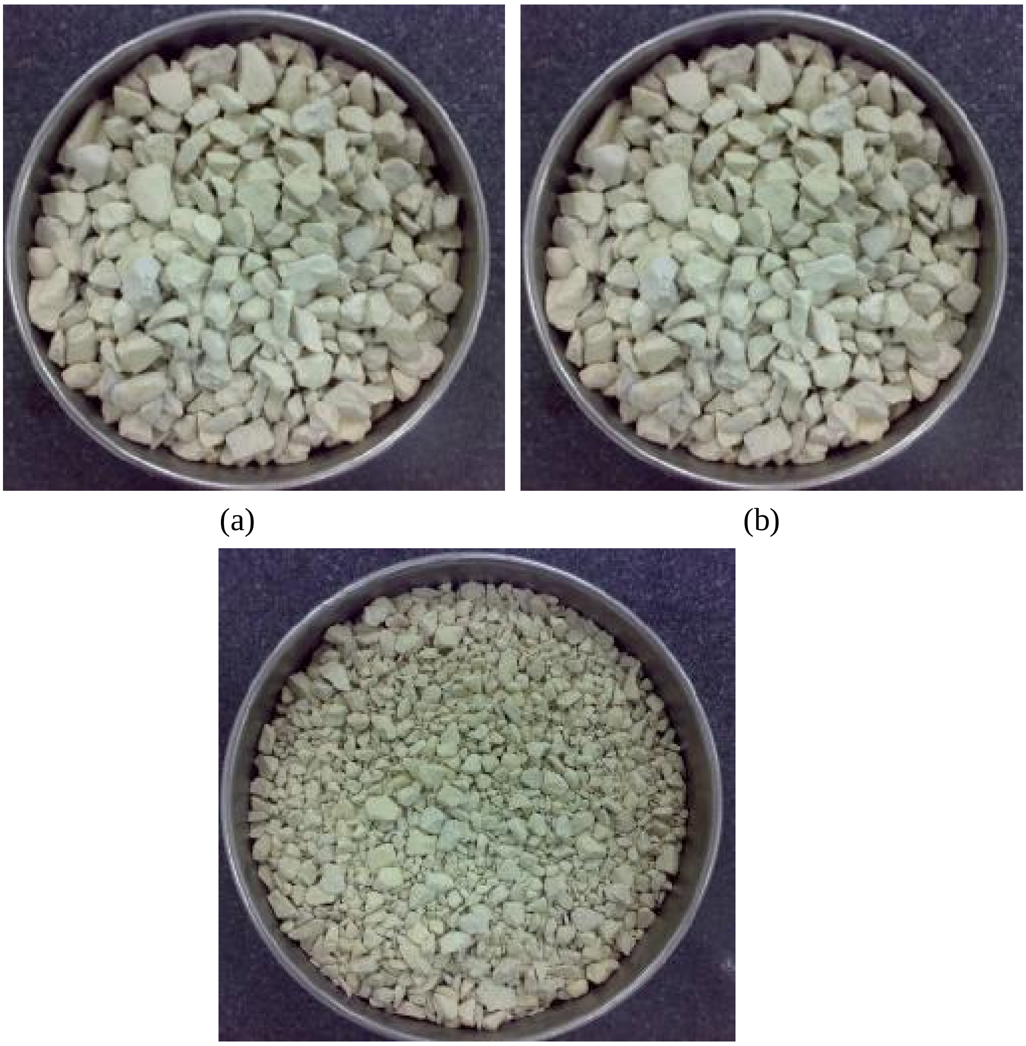
In some concrete mixes, a workability admixture was used to study some variables. The aim of using admixture was only to enhance workability by increasing slump value without changing the water-cement ratio. The type of admixture was super-admixture type Flummox 871-Draco.

4.1.4 Natural Aggregates:

Two main categories of aggregate were used, coarse and fine aggregates. The classification of aggregate into fine and course is referred to ASTM C33 [34].

4.1.4.1 Natural Coarse aggregate:

The coarse aggregate in this study was crushed limestone. Three sizes of coarse aggregate were used with maximum nominal size (25mm) and minimum size of 2.63mm. These aggregate are the commonly types used by Gaza concrete manufactures and locally known by Foliya-type1, Adasiya-type2, and Simsymia-type3. The appearance of these aggregate are shown in Figure (4.1)



(a) (b)

(c)

Figure (4.1): Aggregate used in mixtures preparation: (**a**) Aggregate with maximum size 25 mm -19mm (Foliya). (**b**) Aggregate with maximum size 19 mm -9.5mm (Adasiya) (**c**) Aggregate with maximum size 9.5mm- 4.75mm (Simsimiya) .

Several aggregate properties should be known to prepare one cubic meter of concrete. The most important aggregate properties which needed to prepare concrete mixes are:

- **Specific Gravity** : The aggregate specific gravity is a dimensionless value used to determine the volume of aggregate in concrete mixes. Table (4.1) illustrates the specific gravity value for all natural coarse aggregate which used in the preparation of concrete mixes. The determination of specific gravity of coarse and fine aggregate was done according to ASTM C 127 and ASTM C128 respectively, [35,36]. The specific gravity was calculated at two different conditions which are dry and saturated surface dry conditions.

Table (4.1): Aggregate specific gravity

Aggregate type	G_{sb} (dry)	G_{sb} (SSD)
Type 1(25mm)	2.68	2.71
Type 2 (19mm)	2.59	2.65
Type 3 (9.5mm)	2.52	2.63

- **Moisture content:** The aggregate moisture content is the percentage of water present in a sample of aggregate either inside pores or in the surface. Moisture content of coarse and fine aggregate was done according to ASTM C 566 [37]. The moisture content was 0 .23% for all types.
- **Unit weight :**The unit weight or bulk density of aggregate is the weight of aggregate per unit volume. The bulk density value is necessary to select concrete mixtures proportions. ASTM C 29 procedure was used to determine aggregate bulk density [38]. Table (4.2) illustrates the aggregate unit weight values.

Table (4.2): Aggregate Dry unit weight

Aggregate type	Dry unit weight γ_{dry} (kg/m^3)	SSD unit weight γ_{SSD} (kg/m^3)
(25mm)	1435	1451
(19mm)	1505	1541
(9.5mm)	1485	1530

- **Aggregate absorption:** Absorption of aggregate is the weight of water present in aggregate pores expressed as percentage of aggregate dry weight. ASTM C127 was used to determine coarse aggregate absorption and ASTM C128 for fine aggregate. Table (4.3) illustrates the absorption percentages of all aggregates.

Table (4.3): Aggregate absorption

Aggregate type	Absorption (%)
(25mm)	1.12
(19mm)	2.42
(9.5mm)	3.00

- **Grading and sieve analysis:** The sieve analysis of aggregate includes the determination of coarse and fine aggregate by using a series of sieves. ASTM C136 procedure was used to determine the sieve analysis of coarse and fine aggregate [39].

Table (4.4) shows the sieve grading of the three types of coarse aggregates and shows the maximum and minimum passing limits according to ASTM C33-03.It is also noticed in Table(4.4) that the sieve grading for every type of coarse aggregate doesn't fit the requirements of ASTM C33-03. So it can be mixed to fit the requirements of sieve grading. Many trials of changing the weight of every type in the all mix was made to reach the optimum sieve grading of coarse aggregate.

Table(4.4):Sieve grading of natural coarse aggregate types

	ASTM C 33-03		**Aggregate Type**					**Check with standard ASTM**
Sample Description	**min**	**max**	**Type1**	**Check**	**Type2**	**Check**	**Type3**	
SIEVE SIZE (mm)	**% Passing**	**% Passing**	**% Passing**		**% Passing**		**% Passing**	
37.5	100	100	100	O.K.	100	O.K.	100	O.K.
25	100	100	100	O.K.	100	O.K.	100	O.K.
19	90	100	46.74	Not.O.K.	99.2	O.K.	100	O.K.
12.5			3.33		56.3		100	
9.5	20	55	1.42	Not.O.K.	13.22	Not.O.K.	94.3	Not.O.K.
4.75	0	10	1.06	O.K.	3.41	O.K.	25.24	Not.O.K.
2.63	0	5	1.06	O.K.	2.03	O.K.	6.63	Not.O.K.

Table(4.5) and Figure (4.2), show that 7.0% , 68.0% and 25.0% of the total weight of natural coarse aggregate of type 1, type 2 and type3 respectively were mixed ,the mix was well graded.

Table(4.5): Coarse aggregate grading -ASTM C33-03

	Type1	**Type2**	**Type3**	**Standard Grading**		**Check with standard ASTM**
	7.00%	**68.00%**	**25.00%**			
	Coarse Aggregate			**ASTM C 33-03**		
Sample Description	**Mix Of Type (1&2&3)**			**min**	**max**	
Sieve Size (mm)	**% Passing**			**% Passing**	**% Passing**	
37.5	100			100	100	O.K.
25	100			100	100	O.K.
19	95.7			90	100	O.K.
12.5	63.5					
9.5	32.7			20	55	O.K.
4.75	8.7			0	10	O.K.
2.63	3.1			0	5	O.K.

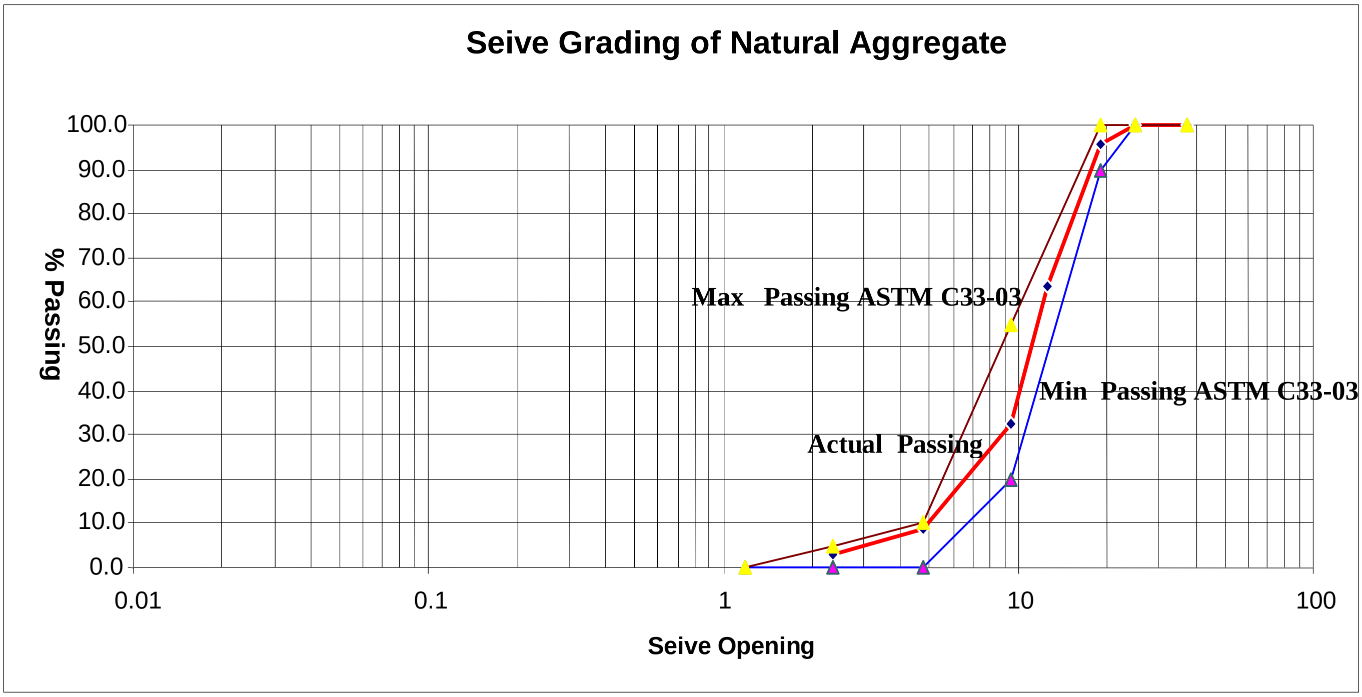


Figure (4.2): Natural coarse aggregate gradation -All in Coarse Aggregate

The physical properties of all in natural coarse aggregates are in Table (4.6). The all in natural aggregates physical properties are calculated by multiplying the percentage of every coarse aggregate type shown in Table(4.5) by its physical property value shown in Tables (4.1),(4.2) & (4.3).

Table(4.6):Natural Coarse Aggregate physical properties

G_{sb} Dry	2.58
G_{sb} SSD	2.65
Absorption %	2.47
Dry unit weight	1495.1 kg/m3
Saturated unit weight	1531.95 kg/m3

4.1.4.2 Natural Fine Aggregates: As defined in ASTM C33-03 fine aggregates is determined according to sieve grading as shown in Table (4.7):

Table(4.7):Fine Aggregate Grading

Sieve No	Opening	ASTM Limits	
	mm	Min	Max
1 1/2"	37.5		
1"	25		
3/4"	19		
1/2"	12.5		
3/8"	9.5	100	100
#4	4.75	95	100
#8	2.36	80	100
#16	1.18	50	85
#30	0.6	25	60
#50	0.3	5	30
#100	0.15	2	10
#200	0.2	0	0

Fineness Modulus (F.M): The use of a single parameter to describe the grading curve can be useful in checking the uniformity of grading. The fineness modulus is such a parameter that can be defined as:

F.M=∑cumulative percent retained on standard sieves (sieves No.4 to No.100) ⁄ 100

The fineness modulus should be between 2.3-3.1.The fineness modulus of fine aggregate is required for mix proportioning [40]. In this study two natural aggregates were used Gaza Strip sand and West Bank crushed stone:

- **Sand:** Sand is a natural material ,and it is avilable in Gaza strip . Sand was tested for physical properties as shown in Table(4.8).The appearance of Gaza sand is shown in Figure(4.3):

Figure (4.3):Sand sample

Table(4.8):Physical Properties of Sand

G_{sb} Dry	2.65
Moisture content	0
Absorption %	0.75
Dry unit weight	1670.01kg/m3

Results of sieving Gaza sand in Table (4.9), indicate that sand is poorly graded according to ASTM C33-03 and at the same time its F.M=1.429 which is less than 2.3, so the sand as afine aggregate should be mixed with other fine aggregates to improve its properties.

Table (4.9):Sieve Grading of Gaza Sand

Sample Description	**Sand**	**ASTM C33-03 Fine AGG.**		**Check with standard ASTM**
Opening (mm)	**% Passing**	**% Passing**	**% Passing**	
9.5	100	100	100	O.K
4.75	100	95	100	O.K
2.36	100	80	100	O.K
1.18	100	50	85	Not. OK
0.6	100	25	60	Not. OK
0.3	52.4	5	30	Not. OK
0.15	4.7	0	10	O.K

Natural Crushed Stone: Crushed stone is a natural material, it is produced as a result of crushing rocks ,and is imported from West Bank. Tables (4.10),(4.11) show physical properties, and sieve grading of crushed stone are shown respectively. The fineness modulus of crushed stone equal 4.36 Which is greater than the allowed for mix proportions.

Table(4.10):Physical Properties of Crushed Stone

G_{sb} Dry	2.65
Absorption %	2.26
Dry unit weight	1610.01kg/m3

Table(4.11):Sieve grading of natural crushed stone

Sample Description	**C. Sand**	**ASTM C33-03 Fine AGG.**		**Check with standard ASTM**
		min	**max**	
Opening (mm)	**% Passing**	**% Passing**	**% Passing**	
9.500	100.00	100.0	100.0	O.K.
4.750	99.03	95.0	100.0	O.K.
2.360	81.92	80.0	100.0	O.K.
1.180	45.93	50.0	85.0	Not.O.K.
0.600	22.30	25.0	60.0	Not.O.K.
0.300	6.97	5.0	30.0	O.K.
0.150	4.15	0.0	10.0	O.K.
0.075	3.26	0.0	7.0	O.K.

Neither Gaza sand nor Crushed stone fits ASTM requirements, so the two kinds are to be mixed. Two options of mixing fine aggregates (Gaza sand) and crushed stone was used to fit ASTM C33-03 specifications and F.M value required for mix design.:

- **First option – Fine-Type 1**: In this option the percent of Gaza sand is 44.4% and the percent of crushed sand is 55.6%.In this option, we tried to minimize the percentage of crushed stone as we can, and the largest percentage of Gaza sand The fine modulus of this option was 2.5.

As shown in Table(4.12) and Figure (4.4), fine type 1 is almost at the extremes of maximum passing required according to ASTM 30 specification which may affect the result.

Table (4.12):Sieve grading fine aggregate-type 1

Sample Description	**C. Sand**	**Sand**	**Total Passing**	**ASTM C33-03 Fine AGG.**		**Check with standard ASTM**
	Percent Of Mixing					
	55.6 %	**44.4 %**		**min**	**max**	
Opening (mm)	% Passing	% Passing	% Passing	% Passing	% Passing	
9.500	100.0	100.0	100.00	100.0	100.0	O.K.
4.750	99.03	100.0	99.46	95.0	100.0	O.K.
2.360	81.92	100.0	89.95	80.0	100.0	O.K.
1.180	45.93	100.0	69.96	50.0	85.0	O.K.
0.600	22.30	100.0	56.84	25.0	60.0	O.K.
0.300	6.97	52.4	27.16	5.0	30.0	O.K.
0.150	4.15	4.7	4.41	0.0	10.0	O.K.
0.075	3.26	0.2	1.91	0.0	7.0	O.K.

Figure (4.4): Sieve grading fine 1

- **Second Option – Fine Type 2:** The percent of sand was reduced to 28.6% of this type which is about half of the sand quantity in fine type 1. The fine modulus is 2.8. As in Table(4.13) and Figure (4.5), it is obvious that the second option is good for mixing concrete fine option since the grading lies between the maximum and minimum values -nearly in the mid area.

Table (4.13):Sieve grading fine aggregate type 2

Sample Description	**C. Sand**	**Sand**	**Cumulative mix**	**ASTM C33-03 Fine AGG.**		**Check with standard ASTM**
	71.40%	**28.60%**		**min**	**max**	
Opening (mm)	**% Passing**	**% Passing**	**% Passing**	**% Passing**	**% Passing**	
9.500	100.00	100.0	100.00	100.0	100.0	O.K.
4.750	99.03	100.0	99.30	95.0	100.0	O.K.
2.360	81.92	100.0	87.08	80.0	100.0	O.K.
1.180	45.93	100.0	61.38	50.0	85.0	O.K.
0.600	22.30	100.0	44.50	25.0	60.0	O.K.
0.300	6.97	52.4	19.95	5.0	30.0	O.K.
0.150	4.15	4.7	4.31	0.0	10.0	O.K.
0.075	3.26	0.2	2.40	0.0	7.0	O.K.

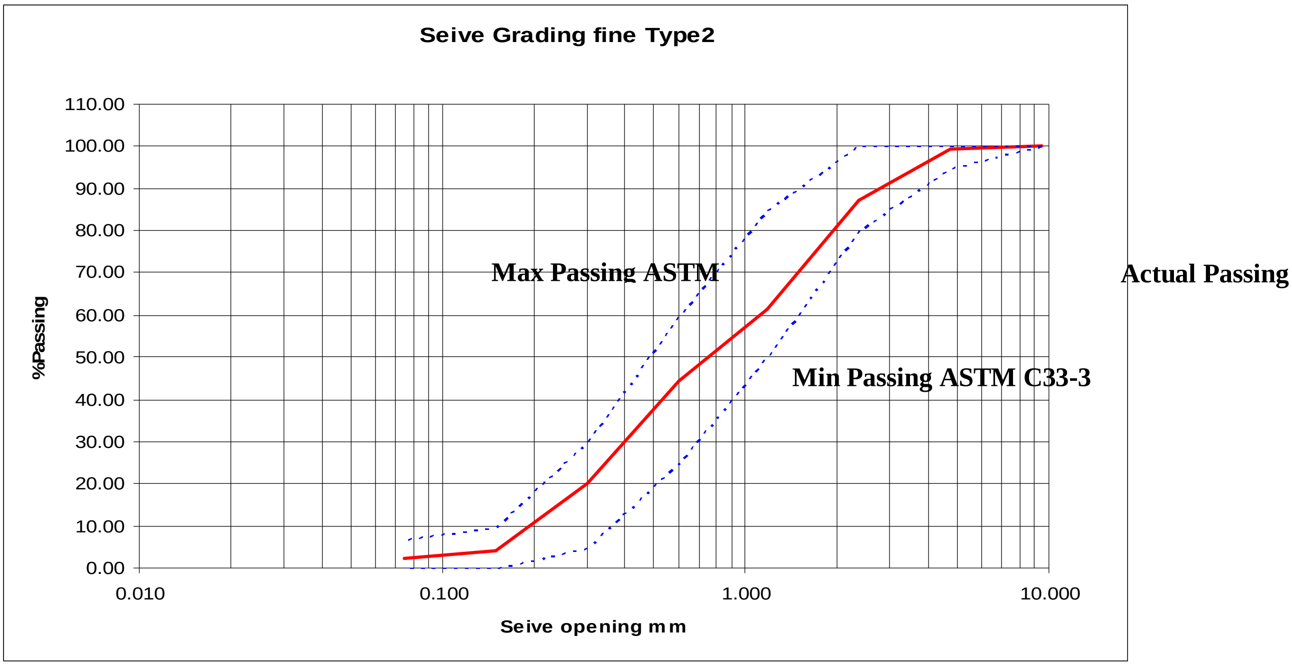


Figure (4.5): Sieve grading fine type 2

4.1.5 Recycled aggregates:

The recycled aggregate is collected from Rafah Municipality at Al Barazeel stock pile site- because the following reasons, maximum size is not much greater than 37.5mm size , good grading and the impurities like bricks ,asphalt ,glass, wood…….etc. were nil..

Recycled coarse aggregate were collected and sieved as shown in Table (4.14). Table (4.14) shows the percentage of fine aggregate; the fine recycled aggregates doesn't exceed 5.0% by weight out of the total amount of recycled aggregates .

Table(4:14):Sieve analysis of all in recycled aggregates collected from Rafah Municipality-Al Barazeel stock pile

Sieve NO.	**Opening mm**	**Retained kg**	**%Passing**
1 1/2"	37.5		
1"	25	0.83	86.69
3/4"	19	1.87	70.03
1/2"	12.5	3.64	41.60
3/8"	9.5	4.62	25.96
#4	4.75	5.75	7.85
#8	2.36	5.945	4.72
#16	1.18	5.98	4.16
#30	0.6	6.01	3.68
#50	0.3	6.07	2.72
#100	0.15	6.155	1.36
#200	0.075	6.195	0.72
Total amount 6.240Kg		6.24	0

Recycled aggregate was separated using standard sieves to two types coarse and fine. Coarse aggregate pass sieve 25mm and retained at sieve 9.5mm, fine aggregates are the aggregates pass sieve 9.5mm-100% opening according to ASTM C33-03.

4.1.5.1 Coarse recycled Aggregate: Same tests and sieve analysis as in natural aggregates were done on coarse recycled aggregates. The physical properties and sieve grading are shown in Tables (4.15),(4.16) . The appearance of coarse recycled aggregate is shown in Figure(4.6) .

Figure(4.6) :A sample of coarse recycled aggregate

- **Physical properties**: Table (4.15) summarizes the physical properties of recycled coarse aggregate :

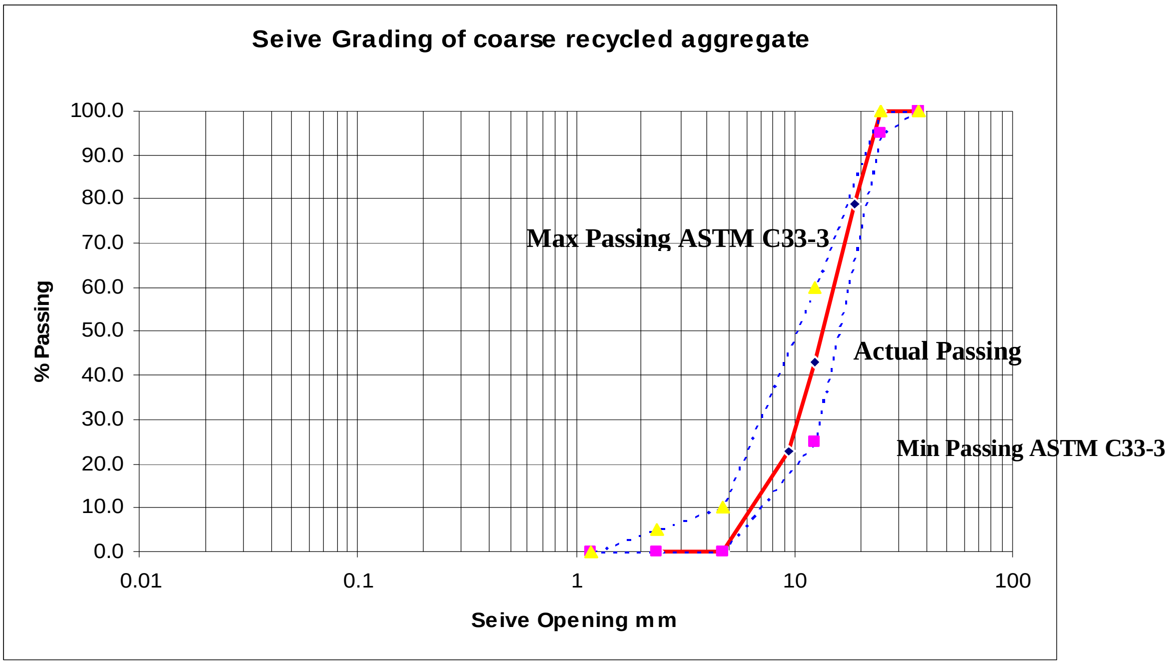
Table (4:15): Recycled Coarse Aggregate physical properties

G_{sb} Dry	2.3
G_{sb} SSD	2.42
Absorption %	5.0
Dry unit weight	1370.0kg/m3
Saturated unit weigh	

Grading and Sieve Analysis: Table (4.16) and Figure(4.7) show the gradation of coarse recycled aggregate . Figure (4.7) shows that the coarse recycled aggregates is good graded ,since it is between the maximum and minimum passing percentage .

Table (4.16): Grading of recycled coarse aggregate

Sample Description	Recycled Coarse Aggregate	ASTMC33-03		Check with standard ASTM
SIEVE SIZE	% Passing	Min	Max	
(mm)				
37.5	100	100	100	O.K.
25	100	100	100	O.K.
19	79.8	90	100	O.K.
12.5	45.4			
9.5	26.4	20	55	O.K.
4.75	4.5	0	10	O.K.
2.63	0	0	5	O.K.



Figure(4.7) :Grading of recycled coarse aggregate

4.1.5.2 Recycled Fine Aggregates: The fine aggregate was separated from the total amount of recycled aggregate . The fine aggregates sieve analysis is shown in Tables (4.17).

Table (4:17): Fine recycled aggregate sieve grading Table

Sieve	Opening	Fine Recycled Aggregate	Specification		Check with standard ASTM
NO	mm	% Passing	Min	Max	
1 1/2"	37.5	100.0			
1"	25	100.0			
3/4"	19	100.0			
1/2"	12.5	100.0			
3/8"	9.5	100.0	100	100	Not.Ok
#4	4.75	28.5	95	100	Not.Ok
#8	2.36	15.9	80	100	Not.Ok
#16	1.18	13.7	50	85	Not.Ok
#30	0.6	11.7	25	60	Not.Ok
#50	0.3	7.9	10	30	Not.Ok
#100	0.15	2.5	2	10	Ok
#200	0.075	0.0	0	0	Ok

From Table (4.17), the recycled fine aggregate is poorly graded; it needs to be mixed with other fine aggregates to improve its grading. Also its quantity is very small about 5.0% of the total amount of recycled aggregate, therefore, the fine recycled aggregate was excluded from concrete mixes.

- **Comparison between coarse recycled and coarse natural aggregate:** Results in Figure (4.8) and Tables(4.6,4.15) indicated that:
    1. Recycled aggregate has rough – textured, angular and elongated particles where natural aggregate is smooth and rounded compact aggregate.
    2. Recycled aggregate is well graded as natural aggregate.
    3. The water absorption capacity of coarse recycled aggregate is 5.0% which is about two times more than natural coarse aggregates.
    4. The dry density of coarse recycled aggregate is lower than dry density of natural aggregate.

The difference is due to cement paste adhered to aggregate and some kinds of impurities in recycled aggregate .The rough – texture, angular and elongated particles require more water than the smooth surface which increase the capacity of water absorption .The void content will increase with the angular aggregate which decrease the dry density of coarse recycled aggregate.

(a) (b)

Figure (4.8):Texture comparison between coarse natural aggregate and coarse recycled a) Natural coarse aggregate b)Recycled coarse aggregate

4.2 Mix preparation

In this study, The mix proportions were prepared according to ACI 211.1 as shown in appendix (A). Four targeted groups of samples were chosen in this study with compressive strtength,B250, B300,m B350 and B400 . Five samples for every targeted group also were prepared to be tested for compressive strength at 7 and 28 days. Three specimens were prepared for pull out test and the same number for flexural test, these specimens were tested at age 28 day.

Concrete containing recycled aggregate has to comply with the same requirements as concrete made with natural aggregate.

The mix operation of concrete for all samples was taken place in a conventional blade-type mixer according to ASTM C192, [41]. Table (4.18) summarized the mix operation procedure which followed for natural aggregate and recycled aggregate concrete mixes.

Table (4.18): Mixing procedure according to ASTM C 192.

Step Number	Description
1	Prior to start mix, add coarse aggregate, some of mixing water which may contain admixture if required
2	Start mixer
3	Add fine aggregate contained, cement, and remaining water with mixer running
4	With all ingredients in the mixer, mix for 3 minutes
5	Stop mixing for 3 minutes
6	Mix for 2 minutes

4.3 Mix proportions

All the mixes was designed for slump 80-100 mm, and designed for the same air content of 0.015 per unit volume. The same water, cement and admixtures were used in all mixes, the variable material is the coarse and fine aggregate type. The proportions used in preparing the various mixes are shown Table (4.19) to Table (4.23):

1-Mix A:

The proportions in this mix was designed using fine aggregates type (1) , (F.M=2.5), and recycled aggregate as a coarse aggregate .Concrete with compressive strength of 250 Kg/cm^2 and 300 kg/cm^2 were prepared for compressive strength test as shown in the following Table (4.19)

Table (4.19): Mix A Proportions

Material Description	Material Source	Maximum Size /Type	Condition	B250	B300
				Weight kg/m^3	Weight kg/m^3
Cement	Nisher Type I, Silos	Type I	Dry	319.67	360
Coarse Recycled Aggregate	Gaza Strip-Rafah-Barazeil stock pile	25mm	1.17% Moisture	975.3	975.3
Natural Fine 1 Crushed aggregate	Crushed Limestone	9.5 mm	.45% Moisture	364.3	355.9
Natural Fine1 - sand	Gaza sand	0.6mm	Dry	291.6	284.6
Free water	University lab water	Tap	Liquid	235.45	232.5
Additives		-	-	No	No
Total weight				2186.32	2208.3

2-Mix B:

The same mix design used in mix A is used in mix B, but all the quantity of fine aggregate is replaced by Gaza sand . Concrete with compressive strength of 250 Kg/cm^2 and 300 kg/cm^2 were prepared for compressive strength test as shown in Tables (4.20).

Table (4.20): Mix B Proportions

Material Description	Material Source	Maximum Size /Type	Condition	B250	B300
				Weight kg/m^3	Weight kg/m^3
Cement	Nisher Type I, Silos	Type I	Dry	319.67	360
Coarse Recycled Aggregate	Gaza Strip-Rafah-Barazeil stock pile	25mm	1.17% Moisture	975.3	975.3
Natural Fine 1 Crushed aggregate	Crushed Limestone	9.5 mm	.45% Moisture	0.0	0.0
Natural Fine1 -sand	Gaza sand	0.6mm	Dry	655.85	640.5
Free water	University lab water	Tap	Liquid	235.45	232.5
Additives		-	-	No	No
Total weight				2191.21	2211.21

3-Mix C :

The proportions of mixing in this set of testing was designed using fine aggregates fine type (2) with F.M=2.8 and recycled aggregate as a coarse aggregate. Concrete with compressive strength of 250 Kg/cm^2 , 300 kg/cm^2 , 350 kg/cm^2 and 400 kg/cm^2 were prepared for compressive strength test as shown in the following Tables (4.21)

Table (4.21): Mix C Proportions

Material Description	**Material Source**	**Maximum Size /Type**	**Condition**	**B250**	**B300**	**B350**	**B400**
				Weight kg/m^3	**Weight kg/m^3**	**Weight kg/m^3**	**Weight kg/m^3**
Cement	Nisher Type I, Silos	Type I	Dry	319.67	361.1	414.9	464.29
Coarse Recycled Aggregate	Gaza Strip-Rafah-Barazeil stock pile	25mm	1.17% Moisture	933.5	933.5	933.5	933.5
Natural Fine2 Crushed aggregate	Crushed Limestone	9.5 mm	.45% Moisture	501	486.7	447.6	417
Natural Fine2 - sand	Gaza sand	0.6mm	Dry	200	195	179	167
Free water	University lab water	Tap	Liquid	236	235.6	233.61	232.12
Additives		-	-	No	No	Yes	Yes
Total weight				2188.71	2210.71	2208.61	2216.67

In the previous mix proportions mix A, mix B and mix C the recycled coarse aggregate constitutes about 60% of the total aggregate used in mix proportions.

4- Mix D

The proportions of mixing in this test was designed using fine aggregates type (2) with F.M=2.8 .The coarse aggregate in this mix was 50% recycled coarse aggregate and 50% natural aggregate. Since sieve grading of both kinds of coarse aggregate in this mix fits the requirements of sieve grading according to ASTM C33, consequently the all in coarse aggregate fits the requirements of ASTM C33. In mix D the coarse recycled aggregate was about 30 %.The mix proportions are shown in Table (4.22).

Table (4.22): Mix D Proportions

Material Description	Material Source	Maximum Size /Type	Condition	B250	B300	B350	B400
				Weight kg/m^3	Weight kg/m^3	Weight kg/m^3	Weight kg/m^3
Cement	Nisher Type I, Silos	Type I	Dry	319.67	361.1	414.9	464.29
Coarse Recycled Aggregate	Gaza Strip-Rafah-Barazeil stock pile	25mm	1.17%	466	466	466	466
Coarse Aggregate type 1	Crushed Limestone	25mm	Saturated	33.2	33.2	33.2	33.2
Coarse Aggregate ype2	Crushed Limestone	19mm	Saturated	322.54	322.54	322.54	322.54
Coarse Aggregate type3	Crushed Limestone	9.5mm	Saturated	117.8	117.8	117.8	117.8
Natural Fine 2 Crushed aggregate		9.5mm	.45% Moisture	556.4	529.45	518.51	497.45
Fine sand 2	Gaza Dune sand	0.6mm	Dry	220.8	218.7	201.5	189.12
Free water	University lab water	Tap	Liquid	219.9	218.93	218.65	218.3
Additives	-	-	-	No	No	Yes	Yes
Total weight				2256.31	2267.72	2293.1	2308.7

5-Mix E

Mix E is used as a control mix ,natural coarse aggregates and fine aggregate type 2 is used (coarse aggregate is saturated) , the proportions is shown in Table (4.23) .

Table (4.23): Mix E Proportions

Material Description	Material Source	Maximum Size /Type	Condition	Weight kg/m^3	Weight kg/m^3	Weight kg/m^3	Weight kg/m^3
Cement	Nisher Type I, Silos	Type I	Dry	319.67	361.1	414.9	464.29
Coarse Aggregate type 1	Crushed Limestone	25mm	Saturated	66.5	66.5	66.5	66.5
Coarse Aggregate ype2	Crushed Limestone	19mm	Saturated	646.2	646.2	646.2	646.2
Coarse Aggregate type3	Crushed Limestone	9.5mm	Saturated	237.6	237.6	237.6	237.6
Natural Fine 2 Crushed aggregate	Crushed Limestone	9.5mm	.45% Moisture	616.0	591.87	559.43	529.3
Fine sand 2	Gaza Dune sand	0.6mm	Dry	246.5	236.7	223.67	211.93
Free water	University lab water	Tap	Liquid	208	207.4	206.8	206.18
Additives	-	-	-	No	No	Yes	Yes
Total weight				2340.7	2347.37	2355	2362

4.4 Test program

The chart in Figure (4.9) summaries the experiments and steps carried out in this work to study the effect of recycled aggregate on concrete properties.

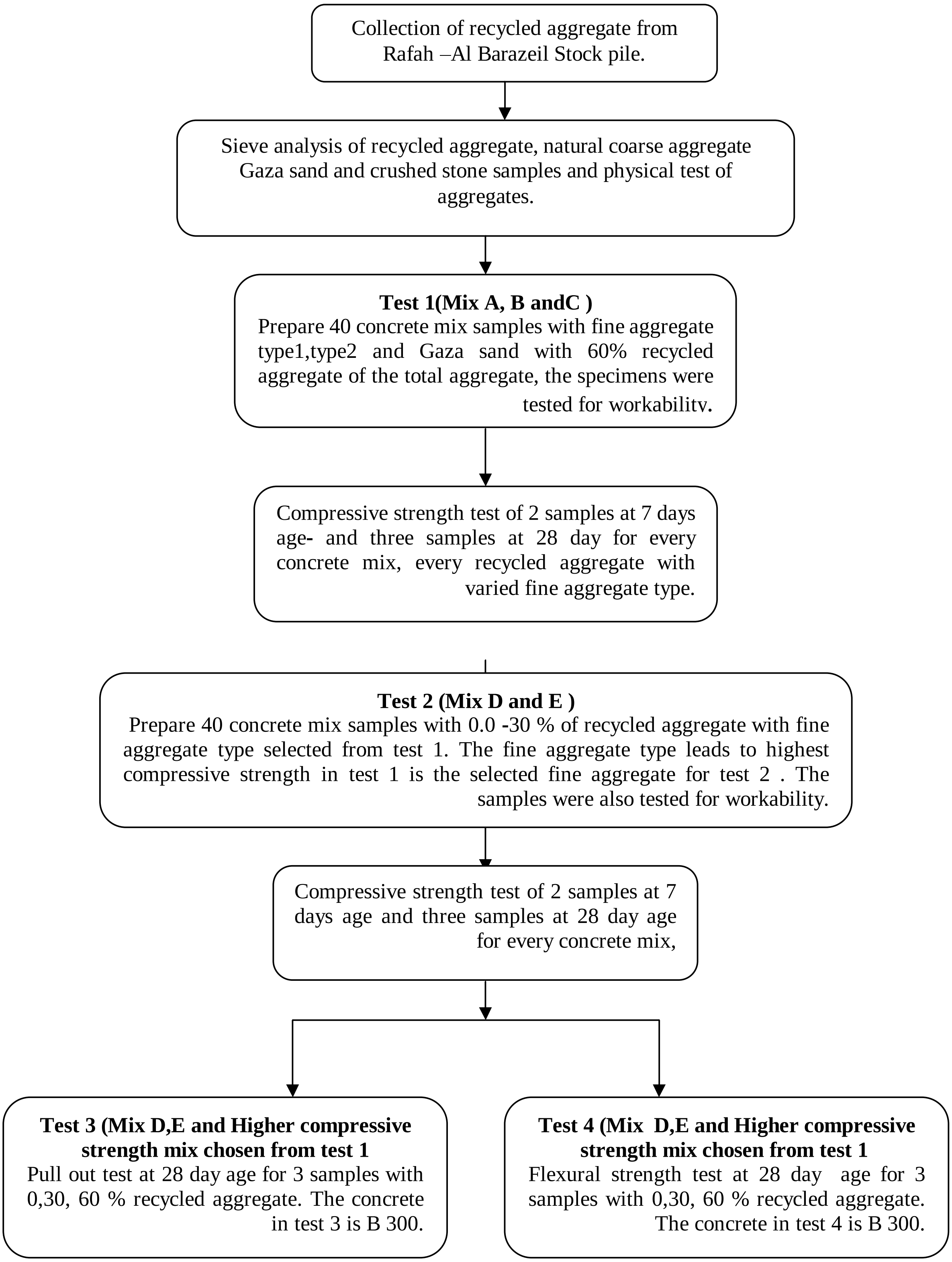


Figure (4.9): The chart of test program steps

This study concentrated on the optimum percent of recycled aggregate and the optimum percent of fine types in concrete mixes to provide valuable recycled aggregate concrete strength.

The study concentrated on developing the most straightforward mix design and preparation techniques to produce recycled aggregate concrete with acceptable properties in fresh and hardened states. The influence of recycled aggregate on concrete properties was studied by preparing several concrete mixes involving different type of compressive strength and different amount of recycled aggregate with different fine aggregate mixes. In this work three percentage of recycled aggregate, 60%, 30%, 0.0% and two types of natural fine aggregate fine type1 and fine type2 were used in concrete mixes. The concrete specimens will be tested at 7 and 28 day. The use of 60 % coarse recycled aggregate and fine types on concrete mixes can be summarized as in Table(4.24):

Table (4.24): Test program of choosing the type of fine aggregates for concrete of 60 %coarse recycled aggregate (test 1 and test 2)

Mix Name	**%recycled aggregate**	**Fine Type**	**No. of Test samples(100*100*100 mm) For targeted Compressive Strength**			
			B 250	**B300**	**B350**	**B400**
Mix A	60	1	5	5	_	_
Mix B	60	Gaza Sand	5	5	_	_
Mix C	60	2	5	5	5	5
Mix D	30		5	5	5	5
Mix E	0		5	5	5	5

The fine aggregate type leads to higher compressive strength in mix A,B or mix C is selected to be used in mix D and mix E .

For the same targeted compressive strength 300 kg/cm^2 , three concrete mixes of the same fine aggregate type were selected from test 1 with 0%,30% and 60% percentages of coarse recycled aggregate. The specimens were prepared to study the behavior of recycled aggregate concrete in flexural strength and bond strength between concrete and steel. The specimens will be tested at age 28 day .Table (4.25) summarizes test 3 and test 4 procedure

Table (4.25): Test program of flexural strength and bond strength of 0,30, &60 % recycled aggregate (Test 3 and test 4)

Mix Name	**%recycled aggregate**	**Fine Type**	**Test 3 -Pull out test(bond between steel and concrete) cube (150.0*150.0*150.0 mm) and steel barØ12 of 550.0mm length**	**Test 4-Flexural test (500*100*100 mm)**
Mix C	60		3	3
Mix D	30		3	3
Mix E	0		3	3

The influence of recycled aggregate on concrete properties were evaluated by studying the concrete properties in fresh and hardened states. In fresh state, the mix workability was evaluated by using slump test and in the hardened states the compressive strength, flexural and pull out test were tested..

4.5 Equipment and testing procedure

4.5.1Density

In this research, the density of concrete specimens were the theoretical density and it was calculated by dividing the weight of each cube on the cube volume. The same cube specimens which used to determine compressive strength were used to determine the density.

4.5.2Workability

Slump test was conducted to asses the workability of fresh control concrete and concrete containing recycled aggregate. The slump test was carried out according to ASTM C143, [42]. For each mix in the test program, a sample of freshly mixed concrete is placed and compacted by rod in a frustum of cone mold as shown in Figure(4.10). The slump value is equal to vertical distance between the original and displaced position of the center of the top surface of the concrete after raising a mold.

Figure (4.10): Slump value determination

4.5.3Compressive strength

All batches discussed before in the experimental program were prepared, cured, and tested for compressive strength at 7and 28day. Standard 100mm cubes were used for compressive strength. The cubes were filled with fresh concrete in two layers and each layer was tamped 25 times with a tamping rod. Immediately after prepared cubes, the specimens were covered to prevent water evaporation.

As shown in Figure (4.11), two identical specimens were crushed at 7days and three identical specimens were crushed at 28 days . The compressive strength was calculated by dividing the failure load by average cross sectional area. The average value of the three specimens at 28 days was considered as the compressive strength of the experiment.

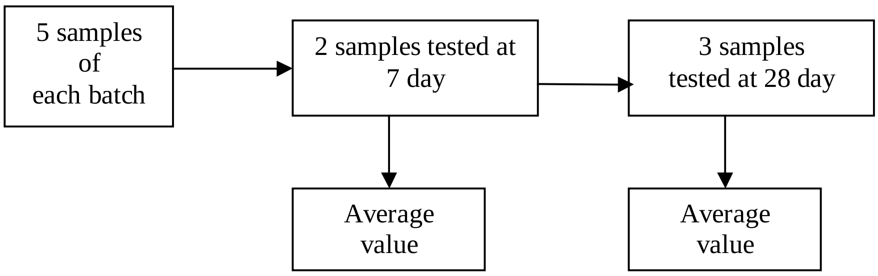


Figure (4.11): Compressive strength evaluation chart of concrete cube specimens

The compressive strength machine in Soil and Material Laboratory at the Islamic University in Gaza was used for determining the maximum compressive loads carried by concrete cubes. The machine was calibrated, adjusted and compared its results to another machine at the Association of Engineering Laboratory to ensure its accuracy. The compressive strength test machine which used in all tests is shown in Figure (4.12).

Figure (4 :12): Compressive strength test machine

4.5.4 Flexural strength

The same machine shown in Figure (4.12) was used to test the beam specimens casted for flexural strength tests; improvements was used to enable the compression test machine to be used for flexural tests as shown in Figure(4.13) . Two rods of 10 mm in diameter at a distance of 400cm was used as a roller supports and one rod of same diameter was used to concentrate the compressive load on the beam specimens.

Figure (4.13):Flexural strength test machine

Standard beam specimens (500*100*100 mm) was used in casting concrete as shown in Figure (4.14) .As shown in Figure (4.15), only one curing test periods at 28 day age was used to examine the flexural strength. Three samples were tested at the specified age. The average value of the three samples was taken as the flexural strength of the batch.

Figure (4.14):Flexural strength Standard beam specimens

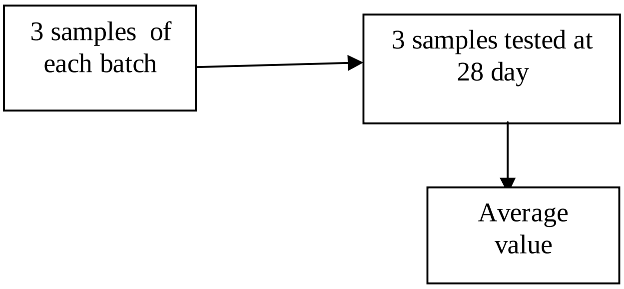


Figure (4.15): Flexural strength evaluation chart for concrete beams samples

Calculations of flexural strength: In flexural test, the tensile stress failure is representative of flexural strength of plain concrete . Figure (4.16) shows the dimensions of flexural test specimens ,the location of supports and the location of the concentrated load .

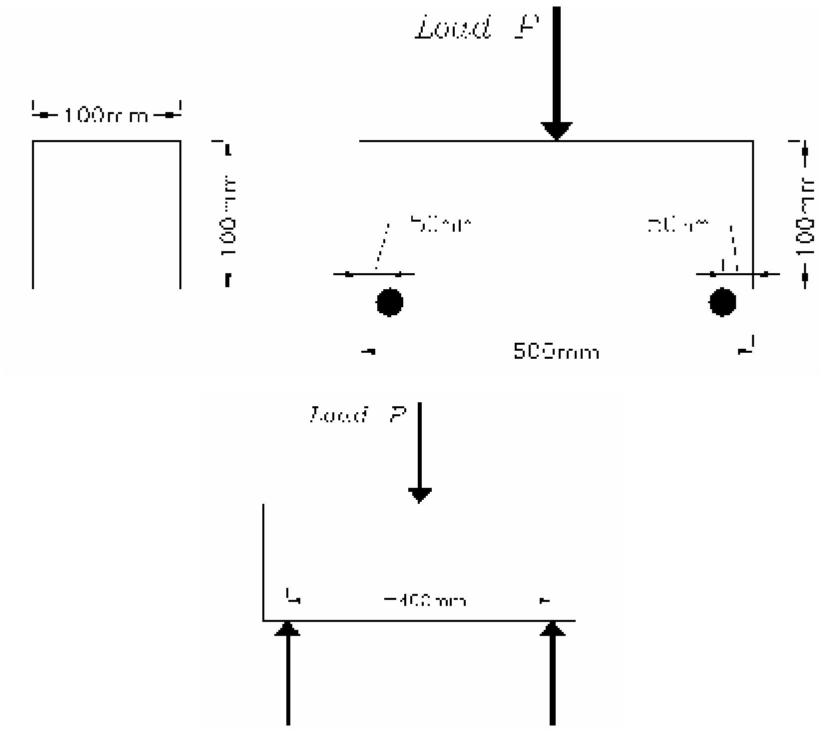


Figure (4.16) : The dimensions of flexural test specimens ,the location of supports and the location of the concentrated load

The tensile stress (σ) is calculated as follows :

Moment failure $M = (P/2)*L/2 = pL/4$

The flexural stress causes failure $\sigma = MC/I$

$= [(pL/4)\ (h/2)\ ]/(bh^3/12)$

P =the reading in the test machine,L =40.0cm (center to center of supports) ,h=10.0 cm (height of cross sectional area) cm, b=10 .0cm (width of cross sectional area)

$\sigma = 3/2[\ (PL)/(bh^2)]$

4.5.5 Pull out test

The machine shown in Figure (4.17) is used to pull out the steel rod from the concrete cubic specimens (150*150*150 mm). The machine and specimens of pull out test that was in this study is approximately similar to what have been used by Jianzhuang Xiao and H. Falkner in their studies in bond strength behavior in 2005 [15] .The specimens in this study were prepared as following:

- Prepare 9 (150*150*15 cm) cubes of concrete mix proportions with 0,30,60 % recycled aggregate
- Deformed Φ12mm steel rods of 550 mm length was immerse in the mid surface of fresh concrete cubes as shown in Figure(4.18) .

Figure (4.17): Pull out test machine

Figure (4.18): Pull out test concrete specimens

The procedure that is used to pull out test is shown in Figure (4.19),where the specimens is placed at the top. The opening at the top just allow for the deformed steel bar to pass ,then the steel bar is pulled down load ,untill the instant of slipping, the digital reading records the splitting load . It is also shown in Figure (4.19) ,that the concrete specimen is not confined, which means that the reading of the machine is a good representative of the bond strength between concrete and steel bars.

Figure (4.19): Procedure of pull out steel rods from concrete specimens

Calculations of pull out test (Bond strength between concrete and steel bars) : Figure (4.20): shows the dimensions of pull out test specimens ,the location and the length of imbedded deformed steel bar in concrete specimens. The bond strength is calculated by dividing the pull out force by the surface area of the embedded length of steal bars s follows:

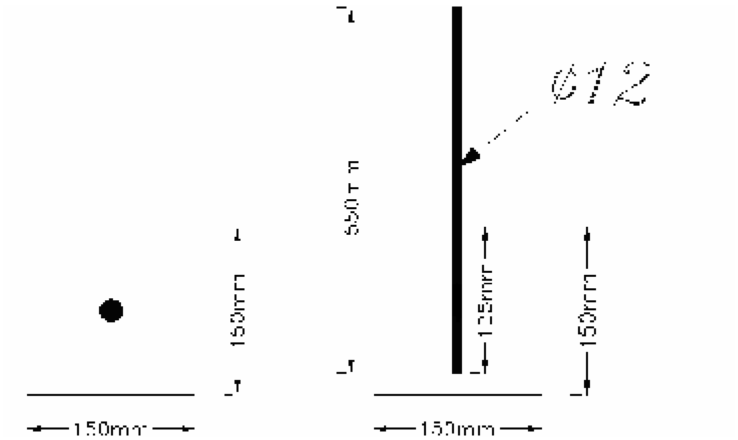


Figure (4.20): The dimensions of pull out test specimens ,the location and the length of imbedded deformed steel bar in concrete specimens

Bond strength =P/(π*D*L)

P: pull out load ,D :diameter of steel rod 1.2cm ,L :embedded length cm

As shown in Figure (4.21), only one curing test periods were used to examine the flexural strength, this period was 28 day. Three samples were tested at the specified age. The average value of the three samples was taken as the compressive strength of the batch.

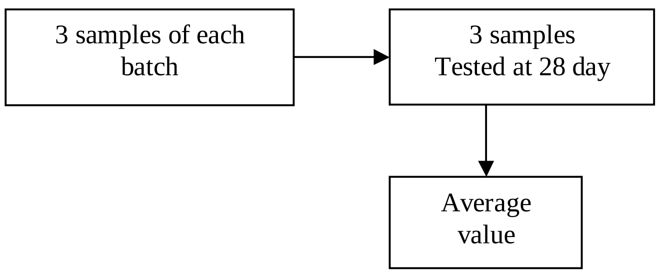


Figure (4. 20): Pull out evaluation chart for concrete cube samples

4.6 Curing conditions

All concrete samples were placed in curing basin after 24 hours from casting. The samples were remained in curing basin until tested at the specified age. The curing condition of soil and material laboratory basin followed the ASTM C192 standard [41]. The curing water temperature is around 25 ^{o}C. Figure (4.22) illustrates the appearance of curing basin which used in this study.

Figure (4:22): Test curing basin

Chapter (5)

Test Results And Analysis

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Test Results And Analysis

This chapter describes the results of the test program designed to study the properties of the various recycled aggregate concrete mixes as described in the test program. The density, slump test of fresh concrete(workability), compressive strength, , flexural strength and pullout test (bond between concrete and steel) of concrete specimens were discussed to investigate the influence of recycled aggregate on concrete properties.

The two optimum compressive strength mixes of different percent of recycled aggregate in addition to the natural aggregate mix were used to investigate the flexural and bond strength properties.

The average results of 7 day and 28 day compressive strength and the 28 day results of density, flexural and bond strength are illustrated in Tables (5.1 to 5.5) .

5.1 Discussion of test results

Tables(5.1) through (5.5) show the average results of the four tests in this experimental program,density,workability,compressive strength ,flexural strength and bond strength respectively. Workability is measured for fresh concrete but compressive strength results are at 7 day age and at 28 day age. Density, flexural strength and bond strength results are at 28 day age Natural aggregate concrete- Mix E- with fine type aggregate 2 was prepared for all the targeted tests to be as a control mix

The test results of the study, concentrate on the behavior of recycled aggregate in concrete mixes. The quantity of recycled aggregate was calculated according to ACI 211.1 code provisions . From mix A,B and C the percent of recycled coarse aggregate is about 60.0%, and from mix D the percent was about 30.0% of the total aggregate.

In this study three types of fine aggregates were used with 60 % recycled coarse aggregate mixes, fine type 1,fine type2 and Gaza sand. Using Fine type 2 leads to optimum compressive strength of 60% coarse recycled aggregate ,so the same type is used in 30 % coarse recycled aggregate (Mix D) and natural coarse aggregate (Mix E). Fine aggregate type 2 as will be shown in Figure (5.2). The physical and mechanical properties were discussed as follows:

5.1.1 Density:

Table(5.1) shows the average 28 day density of concrete specimens for all targeted concrete strength. Figure (5.1) shows the density of concrete mixes at 28 day age versus percentage of coarse recycled aggregate for various water cement ratios .67,.54,.47 and .42.

- Curve A in Figure (5.1) of targeted compressive strength 250 kg/cm2 with water/cement ratio .67 , shows that as the percent of recycled aggregate increases the density of concrete decreases.. Curve A also shows the density of concrete of 60 % recycled aggregate concrete is about 95% of natural aggregate concrete and the density of 30% recycled aggregate is about 96.5% of natural aggregate concrete. The same note for the other curves B,C and D with water cement ratios .54,.47 and .42 was investigated.

Table(5.1) : Average 28 day density of coe specimens for all targeted concrete strength

Target compressive strength (28 day)	B250	B300	B350	B400
Water/cement ratio	0.67	0.54	0.47	0.42
28 day density result (kg/m^3)				
Mix A	2320	2335	_	_
Mix B	2316.3	2325	_	_
Mix C	2271.1	2292.3	2311.8	2322.7
Mix D	2320.1	2341.3	2347.5	2355.23
Mix E	2404.3	2425.9	2432.6	2443.25

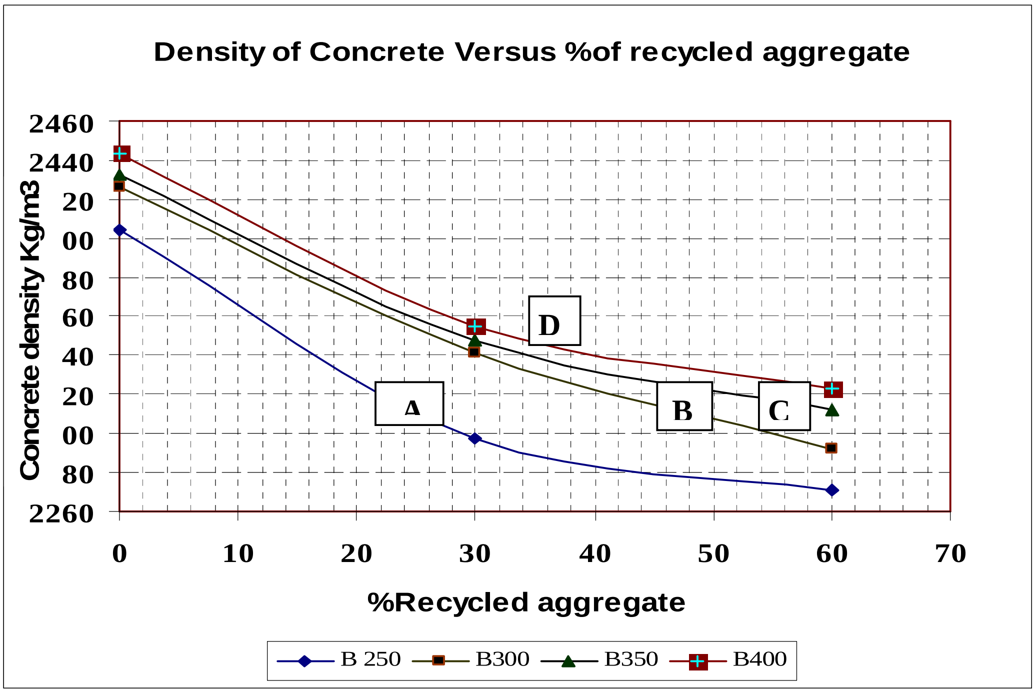

Figure (5.1):Average 28 day concrete density versus percentage of recycled aggregate

The decrease in concrete density when the percent of recycled aggregate in concrete increase can be explained as follows :

- The dry density of recycled aggregate is 1370.0kg/m3, on the other hand the dry density of natural aggregate is 1570.0kg/m3 .
- Recycled aggregate has a rough – textured, angular and elongated particles, which leads to less compacted concrete, where natural aggregate is smooth and rounded compact aggregate.

As shown in Figure (5.2)**,** the density of concrete with 60% recycled aggregate increases when water cement ratio decreases, which is the same behavior of natural aggregate concrete.

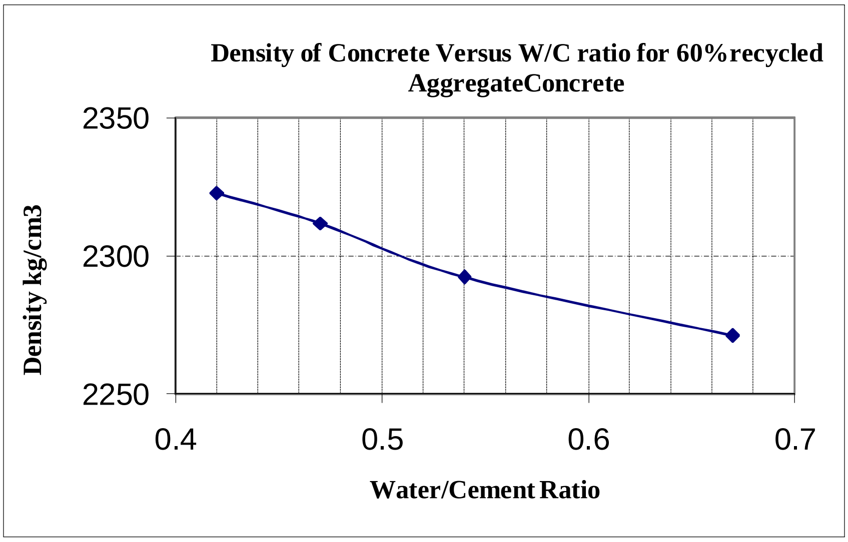

Figure (5.2):Average 28 day concrete density versus water/cement ratio for 60% recycled aggregate concrete

5.1.2 Workability

The slump value was used as indication of mix workability and all the mixes was designed for 80-100mm slump value. Table (5.2), shows a decreasing of workability when the percentage of recycled aggregate increases. The slump was about 1.0cm for recycled aggregate concrete without any admixtures and the slump was about 6.5 cm for natural aggregate concrete.

The effect of recycled aggregate and the percent of Gaza sand on workability is explained as follows :

- The rough – texture, angular and elongated particles due to old existing cement paste requires much water than the smooth aggregate

- Texture of recycled aggregate prevent sliding between aggregate, which leads to low natural compaction

Table (5.2):Average slump value of concrete specimens

	Target compressive strength (28 day)	B250	B300	B350	B400
	Water/ cement ratio	0.67	0.54	0.47	0.42
Mix A	Super plasticizer	No	No	_	_
	Slump result (cm)	0.5	0.5	_	_
Mix B	Super plasticizer	No	No	_	_
	Slump result (cm)	0.5	0	_	_
Mix C	Super plasticizer	No	No	Yes	Yes
	Slump result (cm)	1	0.5	8	9
Mix D	Super plasticizer	No	No	Yes	Yes
	Slump result (cm)	3.5	2	7.5	7
Mix E	Super plasticizer	No	No	Yes	Yes
	Slump result (cm)	7	6.5	9	8.5

5.2.3 Compressive strength:

The compressive strength of concrete is affected by both the aggregate properties, and the characteristics of the new cement paste that is developed during the maturing of concrete. The potential strength of concrete is partially a function of aspects related to mix proportioning such as cement content, water/cement ratio and choice of suitable aggregate but also a function of proper curing when chemical bonding develops. The w/c ratio, proper compaction and adequate curing, affect the development of concrete microstructure, and also affect the amount, distribution and size of pores. The bond that is developed when concrete hardens is the aggregate-paste bond, which is both physical and chemical. The presumption is that recycled aggregate concrete might develop an even weaker chemical bond with cement paste, as the chemical composition of the aggregate is different from those of commonly used natural aggregates and the re-bonding of some elements in cement paste residue can take place.

The most important parameters of the aggregate affecting compressive strength are its shape, texture , maximum size and the strength of coarse aggregate which is one of the dominant factors in classification of concrete aggregate.

Table (5.3):Average compressive strength of concrete specimens

	Target compressive strength (28 day)	B250	B300	B350	B400
	Water/ cement ratio	0.67	0.54	0.47	0.42
Mix A	7 day compressive strength result (kg/cm2)	138.2	198.3	_	_
	28 day compressive strength result (kg/cm2)	212.5	245	_	_
Mix B	7 day compressive strength result (kg/cm2)	128.3	154.1	_	_
	28 day compressive strength result (kg/cm2)	198.5	237	_	_
Mix C	7 day compressive strength result (kg/cm2)	215	239	308.7	366.6
	28 day compressive strength result (kg/cm2)	293.4	334.8	370.7	459.1
MixD	7 day compressive strength result (kg/cm2)	231.1	297.5	310.28	368.9
	28 day compressive strength result (kg/cm2)	325.5	407.6	419.3	505.3
Mix E	7 day compressive strength result (kg/cm2)	266	305.5	390.6	416
	28 day compressive strength result (kg/cm2)	383.9	458.8	484.1	570.6

As in Figure (5.3), the increase of Gaza sand decreases the compressive strength of 60 % recycled aggregate concrete, the optimum compressive strength was achieved by using fine type 2 (28% sand).Using fine type 1 (44.4% sand) and 100% sand caused failing result in mix A and mix B .

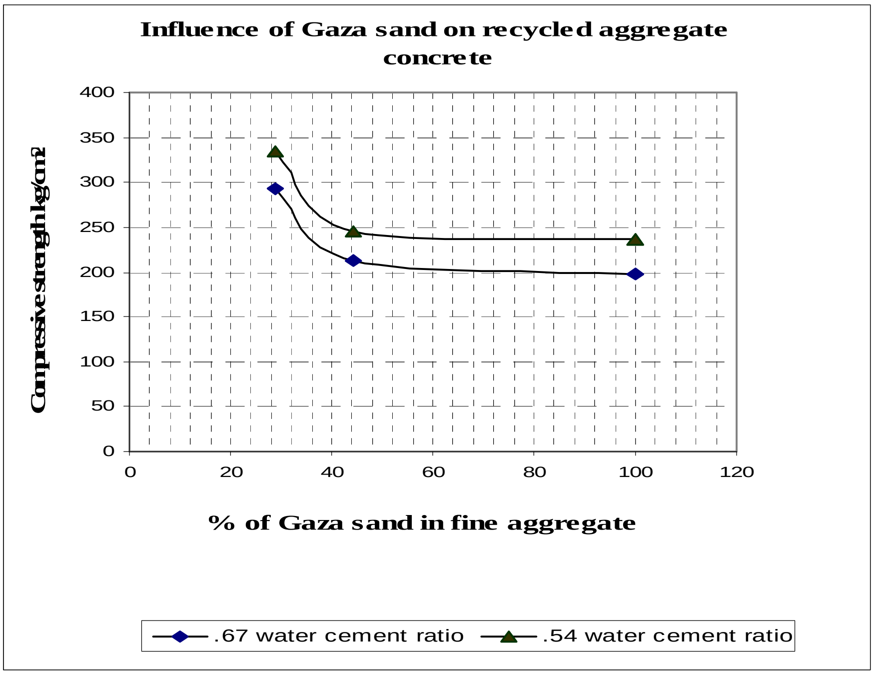

Figure (5.3): Average compressive strength versus % of Gaza sand for the 60.0%of coarse recycled aggregate

The effect of Gaza sand on recycled aggregate concrete is explained as following:

- The increase percent of sand ,increases the surface area of aggregate and consequently more absorption of water, taking in mind high water absorption of recycled aggregate.
- The increase percent of Gaza sand decreases the fine modulus , lower value of fine modulus increases the amount of recycled aggregate according to ACI 211.1 concrete design. The recycled aggregate is weak. Consequently, increasing the amount of recycled aggregate should weaken the compressive strength.
- Poorly grading of sand causes bad integration of all aggregates .

Figure (5.4) shows the influence of recycled aggregate in concrete mixes, optimum results was gained in zero recycled aggregate, the strength of recycled aggregate concrete was lower than the natural aggregate concrete for the same targeted compressive strength concrete. On the average, the recycled aggregate concrete compressive strength was about 75.6% of the natural aggregate concrete compressive strength.

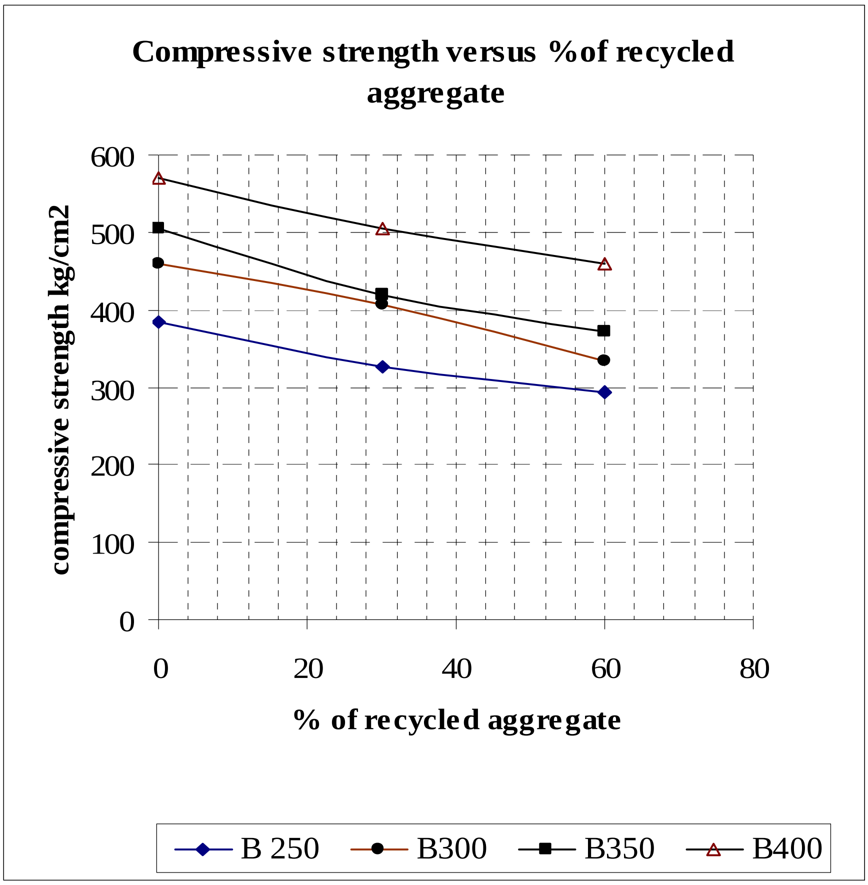

Figure (5.4):Average 28 day compressive strength versus percentage of recycled aggregate for all targeted strength

The decrease of compressive strength due to increase of recycled aggregate percentage can be explained as follows:

- The recycled aggregate is covered with hardened cement paste, which is very weak layer ,so the compressive strength of recycled aggregate it self is weak .
- The hardened cement paste on recycled aggregate is high in water absorption ,consequently no enough residual water is present to complete all the quantity cement reaction .

- The shape of recycled aggregate concrete prevent sliding due to compaction, this leads to not good compaction ,consequently not well compacted concrete.
- The existence of cement paste layer on recycled aggregate prevent integration of all aggregate ,and prevent enough bond between recycled aggregate and new cement paste .
- There was some impurities in the recycled aggregate like wood, glass, bricks ………..etc. which affect the bond in general adversely.

From Table (5.3) the compressive strength of 7day recycled aggregate concrete is about 76 % of 7 days age natural aggregate ,which is the same percent as in 28 days compressive strength . In Figure (5.5) 7 days age compressive strength of recycled aggregate concrete curve is parallel to natural aggregate curve, this means the recycled aggregate concrete behaves like natural aggregate concrete.

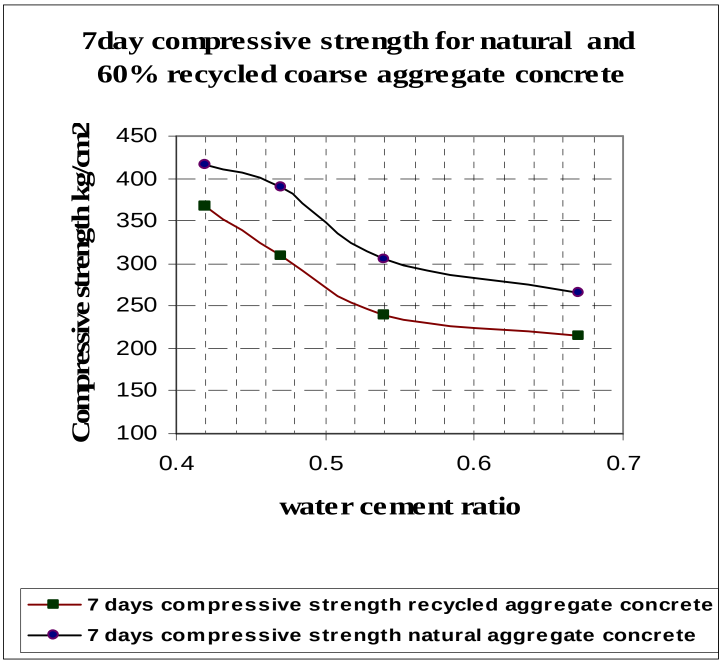

Figure (5.5):7 day average compressive strength versus water/cement ratio for the natural and 60.0% of coarse recycled aggregate

5.2.4 Modulus of rupture _Flexural strength

Table (5.4) and Figure(5.6) show the relationship between recycled aggregate percent and flexural strength for theoretical and actual flexural strength .The flexural strength decreases as the percent of recycled aggregate increases and the flexural strength is well proportioned to compressive strength .The same justifications of compressive strength versus percent of recycled aggregate , is valid for flexural strength .

Table (5.4):Average flexural strength of concrete specimens

	60.0%Recycled aggregate concrete	30.0%Recycled aggregate concrete	0.0%Recycled aggregate concrete
Compressive strength kg/cm2(100*100*100 mm)	327.2	388.7	436.4
Point load failure (**p**) kg	970	1020	1150
Average Flexural(Modulus) rupture) Stress(Kg/cm2) – **σ**	58	61	69
Theoretical Modulus of rupture-(3.18√fckg/cm2) [43]	57.5	62.7	66.4

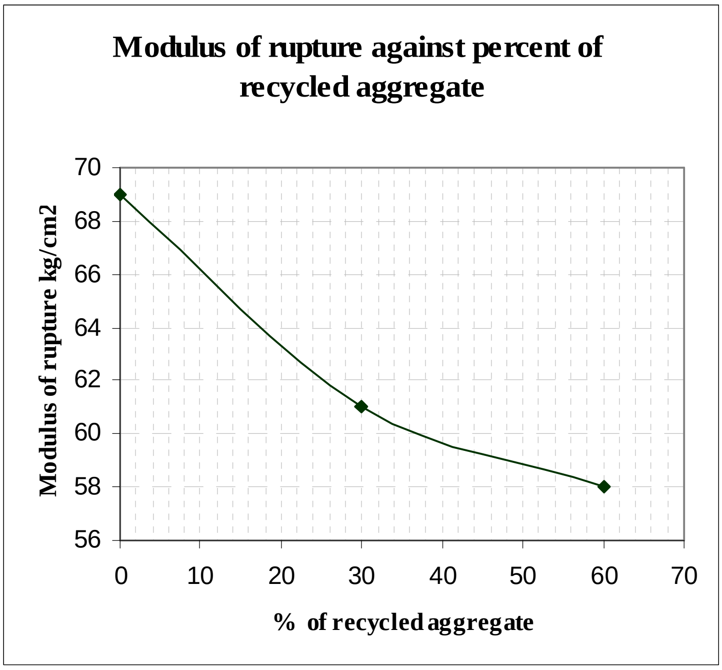

Figure (5.6): Average concrete modulus of rupture versus percentage of recycled aggregate

5.2.5 Bond strength :

As shown in Table (5.5) and Figure (5.6), the bond strength between concrete and deformed steel bars is increasing as the percent of recycled aggregate increases. Under the condition of the equivalent mix proportioned compared with that of normal concrete, the bond strength between the recycled aggregate concrete and the deformed bar increases by 32.4% and 46.1% for a recycled concrete aggregate replacement percentage of 30.0% and 60.0%, respectively. The behavior of deformed bar slipping between recycled aggregate concrete and steel bars similar to the one for normal concrete and steel bars

Table (5.5):Average bond strength of concrete

	60.0%Recycled aggregate concrete	30.0%Recycled aggregate concrete	0.0%Recycled aggregate concrete
Compressive strength kg/cm2	327	345.3	390.7
Pull out(load failure P)kg	5616.7	4964.7	3909.6
length of deformedsteel bar Φ12 anchorage(cm)	12.5	12.5	12.5
Bond Strength Kg/cm2	119.4	108.2	81.7

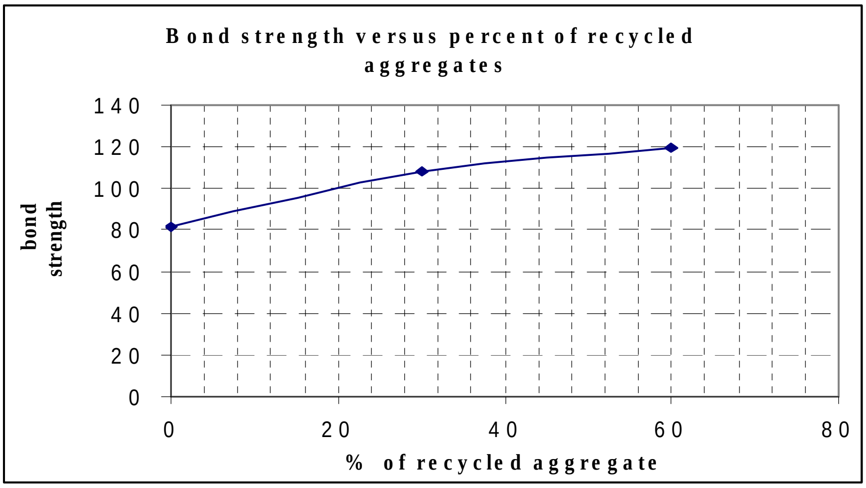

Figure (5.7): Bond strength versus percentage of recycled aggregate

The increase of bond strength between the deformed bars and recycled aggregate concrete is due to :

- Rough surface and angular edges of recycled aggregate increases the friction between deformed bars and recycled aggregate .

5.5 Summary:

The density of recycled aggregate concrete is lower than that of natural aggregate by 5.5% ,this decrease is due to light weight of recycled aggregate and bad compaction because of the nature of recycled aggregate and its texture.

The workability of recycled concrete is reduced because the mortar from the original concrete makes the recycled aggregate more porous and absorptive than its natural counterpart, the absorption capacity of recycled aggregate is more than two times of natural aggregates absorption capacity. The additional absorption requires more water be added to the recycled aggregate stockpile, to reach saturation before it can be added to the concrete mix.

The results of tests of recycled aggregate showed, the recycled aggregate concrete can provide strength almost equivalent to a corresponding concrete with natural aggregates for the same quantity of cement. The use of recycled aggregate does not seriously affect the compressive strength of the concrete when only the coarse aggregates were replaced by coarse fragments of demolition debris. Using 60 % of recycled coarse aggregate in concrete mixes decrease the compressive strength by about 24.6.0%.

The behavior of recycled aggregate concrete is the same as natural aggregate concrete under flexural loading and at the same time the flexural strength of recycled aggregate is proportioned to compressive strength exactly as natural aggregate concrete.

The bond strength is affected positively by using recycled aggregate in concrete mixes where the sharp edges of recycled aggregate increases the friction between deformed bars and concrete. The 60% recycled aggregate concrete bond strength is 1.45 times natural aggregate concrete bond strength.

Finally, the experimental results showed good performance of recycled aggregate in concrete mixes ,approximately equivalent to natural aggregates.

Chapter (6)

Conclusion And Recommendations

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Conclusion And Recommendations

6.1 Introduction

The reuse of recycled materials derived from construction and demolition waste is growing all over the world. Many governments are actively promoting policies aimed at reducing the use of primary resources and increasing reuse and recycling. One of the most environmentally responsible ways of meeting the challenges of sustainability in construction is the use of recycled construction and demolition waste in new construction. Research and experimental works on the use of recycled aggregates have proven that good quality concrete could also be produced with recycled aggregates.

The main objective of the work was to investigate the feasibility of using recycled aggregate in concrete mixes in lieu of natural aggregate. This study included the preparation of concrete mixes containing varied percentages of recycled aggregate, and varied natural fine aggregate properties. Also this study included the evaluation of concrete properties in fresh and hardened states. The studied properties involved mix workability, compressive strength, density, flexural strength and bond strength. According to experimental results, the use of recycled aggregate in concrete mixes as an alternative of natural aggregate is possible. The influence of recycled aggregate on concrete properties was studied.

The following section presents the main conclusion which can be drawn based on the experimental results.

6.2 Main conclusions of the study

Experimental works on the use of recycled aggregates have proven that good quality concrete could be produced with recycled aggregates. The use of aggregates produced from recycled construction and demolition waste should be further promoted. Based on the experimental investigation reported in the work, the following conclusions are drawn:

- The dry density of recycled aggregate is about .85 of the dry density of natural aggregate, the all density of recycled aggregate is about .95 of natural aggregate concrete, which is not much lower than natural aggregate concrete density.
- The workability of recycled aggregate concrete mix is lower than natural aggregate, concrete mix with 30.0% recycled aggregate concrete has satisfied workable concrete. The superplasticiser is considered necessary for achieving the required workability of concrete using more than 30.0% recycled aggregate .

- The compressive strength of concrete increases as the percent of recycled aggregate decreases, on the average, the recycled aggregate concrete cube strength was 74.6% of that of the natural aggregate concrete. At the same time the increase of Gaza sand (Gaza sand is very fine, poorly graded and its fine modulus =1.4) for the same mix proportions of recycled aggregate concrete mix, decreases the compressive strength of concrete cubes 28% less than recycled aggregate uses fine aggregate with less percent of Gaza sand.

- The flexural strength of recycled aggregate was good indicator of the behavior of recycled aggregate concrete, since the flexural strength concrete was proportioned to compressive strength -(3.18√fckg/cm2).
- The bond strength is affected positively when the percentage of recycled aggregate where, the bond strength increases when recycled aggregate increases.
- The recycled aggregate concrete has a convenient compressive strength, flexural strength, and bond strength ,which means a convenient concrete for structural elements in concrete structures.
- Gaza sand cannot be used only as a fine aggregates it should be mixed with crushed sand .

6.3 **Recommendations for further studies**

While studies have shown that recycled concrete aggregate can be used as aggregate for new concrete, there is a need to obtain long-term in-service performance and life cycle cost data for concrete made with recycled aggregate concrete to assess its durability and performance. If additional research supports the use of concrete buildings then existing specification should be revised to permit and encourage the use of recycled concrete as aggregate. Using recycled aggregate in concrete mixes leads to conserve existing supplies of natural aggregates and to reduce the amount of solid waste that must be disposed of in landfills. Further testing and studies on the recycled aggregate concrete is highly recommended to indicate the strength characteristics of recycled aggregates for application in high strength concrete. Below are some of the recommendations for further studies:

- An important step in maintaining and encouraging the recyclability of concrete is the ability to separate other building materials like wood, bricks ,polyethylene products ,minerals etc. from the concrete construction that would either be incompatible in a common preparation process, or would at least restrict the recycling.
- Although by decreasing the water/cement ratio, recycled aggregate can achieve higher compressive strength concrete. But the workability will be very low. Therefore, it is recommended that adding admixtures such as super

plasticizer and silica fume into the mixing so that the workability will be improved

- More investigations and laboratory tests should be done on the strength characteristics of recycled aggregate. It is recommended that testing can be done on concrete slabs, beams and walls. Some mechanical properties such as creeping and abrasion were also recommended.
- More trials with different particle sizes of recycled aggregate and percentage of replacement of recycled aggregate are recommended to get higher strength characteristics in the recycled aggregate concrete
- More investigations and laboratory tests should be done on the durability of recycled aggregate concrete in new concrete, and its creep and shrinkage characteristics.
- The influence of contaminants in the demolished concrete from buildings should be carefully studied and investigated to extend life time of concrete made with recycled aggregate concrete.
- Further studies on the long-term feasibility of recycling.
- The fire-resistant property of recycled aggregates should be carefully studied .
- More studies on the economic aspect of concrete processing and recycling.
- More investigations and laboratory tests should be done on the use of fine recycled aggregates.
- As natural aggregate specification in all codes and building specification all over the world. specifications and standards were found to be key to the future use of recycled aggregates. Work is required to develop specifications and standards in order to create opportunities for the increased use of recycled aggregates.

Chapter (7)

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Appendix (A)

Design of Concrete Mixtures

ACI Method

The American Concrete Institute (ACI) mix design method is but one of many basic concrete mix design methods available today. This section summarizes the ACI absolute volume method because it is widely accepted in the U.S. and continually updated by the ACI. Keep in mind that this summary and most methods designated as "mix design" methods are really just mixture proportioning methods. Mix design includes trial mixture proportioning (covered here) plus performance tests.

This section is a general outline of the ACI proportioning method with specific emphasis on PCC for pavements. It emphasizes general concepts and rationale over specific procedures. Typical procedures are available in the following documents: The American Concrete Institute's (ACI) Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete (ACI 211.1-91) as found in their *ACI Manual of Concrete Practice 2000, Part 1: Materials and General Properties of Concrete*.

- The Portland Cement Association's (PCA) Design and Control of Concrete Mixtures, 14th edition (2002) or any earlier edition.

The standard ACI mix design procedure can be divided up into 8 basic steps:

1. <u>Choice of slump</u>
2. <u>Maximum aggregate size selection</u>
3. <u>Mixing water and air content selection</u>
4. <u>Water-cement ratio</u>
5. <u>Cement content</u>
6. <u>Coarse aggregate content</u>
7. <u>Fine aggregate content</u>
8. <u>Adjustments for aggregate moisture</u>

Slump

The choice of slump is actually a choice of mix workability. Workability can be described as a combination of several different, but related, PCC properties related to its theology:

- Ease of mixing
- Ease of placing
- Ease of compaction
- Ease of finishing

Generally, mixes of the stiffest consistency that can still be placed adequately should be used (ACI, 2000). Typically slump is specified, but Table A-1 shows general slump ranges for specific applications. Slump specifications are different for fixed form paving and slip form paving. Table A-2 shows typical and extreme state DOT slump ranges.

Type of Construction	**Slump**	
	(mm)	**(inches)**
Reinforced foundation walls and footings	25 - 75	1 - 3
Plain footings, caissons and substructure walls	25 - 75	1 - 3
Beams and reinforced walls	25 - 100	1 - 4
Building columns	25 - 100	1 - 4
Pavements and slabs	25 - 75	1 - 3
Mass concrete	25 - 50	1 - 2

Table (A-1): Slump Ranges for Specific Applications (after ACI, 2000)

Specifications	**Fixed Form**		**Slip Form**	
	(mm)	(inches)	(mm)	(inches)
Typical	25 - 75	1 - 3	0 - 75	0 - 3
Extremes	as low as 25 as high as 175	as low as 1 as high as 7	as low as 0 as high as 125	as low as 0 as high as 5

Table (A-2): Typical State DOT Slump Specifications (data taken from ACPA, 2001)

Maximum Aggregate Size

Maximum aggregate size will affect such PCC parameters as amount of cement paste, workability and strength. In general, ACI recommends that maximum aggregate size be limited to 1/3 of the slab depth and 3/4 of the minimum clear space between reinforcing bars. Aggregate larger than these dimensions may be difficult to consolidate and compact resulting in a honeycombed structure or large air pockets. Pavement PCC maximum aggregate sizes are on the order of 25 mm (1 inch) to 37.5 mm (1.5 inches) (ACPA, 2001).

Mixing Water and Air Content Estimation

Slump is dependent upon nominal maximum aggregate size, particle shape, aggregate gradation, PCC temperature, the amount of entrained air and certain chemical admixtures. It is not generally affected by the amount of cementitious material. Therefore, ACI provides a table relating nominal maximum aggregate size, air entrainment and desired slump to the desired mixing water quantity. Table (A-3) is a partial reproduction of ACI Table 6.3.3 (keep in mind that pavement PCC is almost always air-entrained so air-entrained values are most appropriate). Typically, state agencies specify between about 4 and 8 percent air by total volume (based on data from ACPA, 2001).

Note that the use of water-reducing and/or set-controlling admixtures can substantially reduce the amount of mixing water required to achieve a given slump.

	Mixing Water Quantity in kg/m^3 (lb/yd^3) for the listed **Nominal Maximum Aggregate Size**							
Slump	**9.5 mm (0.375 in.)**	**12.5 mm (0.5 in.)**	**19 mm (0.75 in.)**	**25 mm (1 in.)**	**37.5 mm (1.5 in.)**	**50 mm (2 in.)**	**75 mm (3 in.)**	**100 mm (4 in.)**
Non-Air-Entrained PCC								
25 - 50 (1 - 2)	207 (350)	199 (335)	190 (315)	179 (300)	166 (275)	154 (260)	130 (220)	113 (190)
75 - 100 (3 - 4)	228 (385)	216 (365)	205 (340)	193 (325)	181 (300)	169 (285)	145 (245)	124 (210)
150 - 175 (6 - 7)	243 (410)	228 (385)	216 (360)	202 (340)	190 (315)	178 (300)	160 (270)	-
Typical entrapped air (percent)	3	2.5	2	1.5	1	0.5	0.3	0.2
Air-Entrained PCC								
25 - 50 (1 - 2)	181 (305)	175 (295)	168 (280)	160 (270)	148 (250)	142 (240)	122 (205)	107 (180)
75 - 100 (3 - 4)	202 (340)	193 (325)	184 (305)	175 (295)	165 (275)	157 (265)	133 (225)	119 (200)
150 - 175 (6 - 7)	216 (365)	205 (345)	197 (325)	184 (310)	174 (290)	166 (280)	154 (260)	-
Recommended Air Content (percent)								
Mild Exposure	4.5	4.0	3.5	3.0	2.5	2.0	1.5	1.0
Moderate Exposure	6.0	5.5	5.0	4.5	4.5	4.0	3.5	3.0
Severe Exposure	7.5	7.0	6.0	6.0	5.5	5.0	4.5	4.0

Table (A-3): Approximate Mixing Water and Air Content Requirements for Different Slumps and Maximum Aggregate Sizes (adapted from ACI, 2000).

Water-Cement Ratio

The water-cement ratio is a convenient measurement whose value is well correlated with PCC strength and durability. In general, lower water-cement ratios produce stronger, more durable PCC. If natural pozzolans are used in the mix (such as fly ash) then the ratio becomes a water-cementitious material ratio (cementitious material = Portland cement + pozzolonic material). The ACI method bases the water-cement ratio selection on desired compressive strength and then calculates the required cement content based on the selected water-cement ratio. Table (A-4) is a general estimate of 28-day compressive strength vs.

water-cement ratio (or water-cementitious ratio). Values in this table tend to be conservative (ACI, 2000). Most state DOTs tend to set a maximum water-cement ratio between 0.40 - 0.50 (based on data from ACPA, 2001).

28-Day Compressive Strength in MPa (psi)	Water-cement ratio by weight	
	Non-Air-Entrained	Air-Entrained
41.4 (6000)	0.41	-
34.5 (5000)	0.48	0.40
27.6 (4000)	0.57	0.48
20.7 (3000)	0.68	0.59
13.8 (2000)	0.82	0.74

Table (A-4): Water-Cement Ratio and Compressive Strength Relationship (after ACI, 2000)

8.5 Cement Content

Cement content is determined by comparing the following two items:

- The calculated amount based on the selected mixing water content and water-cement ratio.
- The specified minimum cement content, if applicable. Most state DOTs specify minimum cement contents in the range of 300 - 360 kg/m^3 (500 - 600 lbs/yd^3).

An older practice used to be to specify the cement content in terms of the number of 94 lb. sacks of portland cement per cubic yard of PCC. This resulted in specifications such as a "6 sack mix" or a "5 sack mix". While these specifications are quite logical to a small contractor or individual who buys portland cement in 94 lb. sacks, they do not have much meaning to the typical pavement contractor or batching plant who buys portland cement in bulk. As such, specifying cement content by the number of sacks should be avoided.

Coarse Aggregate Content

Selection of coarse aggregate content is empirically based on mixture workability. ACI recommends the percentage (by unit volume) of coarse aggregate based on nominal maximum aggregate size and fine aggregate fineness modulus. This recommendation is based on empirical relationships to produce PCC with a degree of workability suitable for usual reinforced construction (ACI, 2000). Since pavement PCC should, in general, be more stiff and less workable, ACI allows increasing their recommended values by up to about 10 percent. Table (A-5) shows ACI recommended values.

Nominal Maximum Aggregate Size	**Fine Aggregate Fineness Modulus**			
	2.40	**2.60**	**2.80**	**3.00**
9.5 mm (0.375 inches)	0.50	0.48	0.46	0.44
12.5 mm (0.5 inches)	0.59	0.57	0.55	0.53
19 mm (0.75 inches)	0.66	0.64	0.62	0.60
25 mm (1 inches)	0.71	0.69	0.67	0.65
37.5 mm (1.5 inches)	0.75	0.73	0.71	0.69
50 mm (2 inches)	0.78	0.76	0.74	0.72

Notes:

1. These values can be increased by up to about 10 percent for pavement applications.
2. Coarse aggregate volumes are based on oven-dry-rodded weights obtained in accordance with ASTM C 29.

Table (A-5): Volume of Coarse Aggregate per Unit Volume of PCC for Different Fine aggregate Fineness Moduli *for Pavement PCC* (after ACI, 2000).

Fine Aggregate Content

At this point, all other constituent volumes have been specified (water, portland cement, air and coarse aggregate). Thus, the fine aggregate volume is just the remaining volume:

Unit volume (1 m^3 or yd^3)
- Volume of mixing water
- Volume of air
- Volume of portland cement
- Volume of coarse aggregate

Volume of fine aggregate

Adjustments for Aggregate Moisture

Unlike HMA, PCC batching does not require dried aggregate. Therefore, aggregate moisture content must be accounted for. Aggregate moisture affects the following parameters:

1. *Aggregate weights*. Aggregate volumes are calculated based on oven dry unit weights, but aggregate is typically batched based on actual weight. Therefore, any moisture in the aggregate will increase its weight and stockpiled aggregates almost always contain some moisture. Without correcting for this, the batched aggregate volumes will be incorrect.

2. *Amount of mixing water*. If the batched aggregate is anything but saturated surface dry it will absorb water (if oven dry or air dry) or give up water (if wet) to the cement paste. This causes a net change in the amount of water available in the mix and must be compensated for by adjusting the amount of mixing water added.

Summary

The ACI mix design method is one of many available methods. It has been presented here to give a general idea of the types of calculations and decisions that are typical in PCC mix design.